MOTION IN THE HEAVENS

Paul Peirce Stief

Physics: A Human Endeavour

Unit 2 Motion in the Heavens

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". . . I believe, basically, we have not been cautious enough of the meaning of science in our generation, to teach it in a way which would be understood and appreciated and felt by the students. We have very little of the positive values of science outside of the applications which are obvious to anybody living in this age. In other words, my claim is, and this is something we should discuss, that we have not been teaching our science in a humanistic way. We have been teaching science at every level, in a certain sense, as a certain bag of tricks which the bright boy or girl could learn and show off with, or at least get a great deal of pleasure out of—the same kind of pleasure, but not quite as sharp, as he would get out of plane geometry.

Now, science is a very different thing . . . it is an adventure of the whole human race to learn to live in and perhaps to love the universe in which they are. To be a part of it is to understand, to understand oneself, to begin to feel that there is a capacity within man far beyond what he felt he had, of an infinite extension of human possibilities—not just on the material side (whatever that may mean, because the more we study the material side, the more and more it recedes) . . .

So what I propose as a suggestion for you is that science be taught at whatever level, from the lowest to the highest, in the humanistic way. By which I mean, it should be taught with a certain historical understanding, with a certain philosophical understanding, with a social understanding and a human understanding in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations."

From the address of I. I. Rabi at AAAS meeting of Educational Policies Commission, 27 December 1966, Washington, D.C.

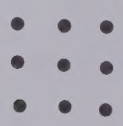
Preface

Physics: A Human Endeavour is an examination of some parts of man's attempt to understand the physical world. We call physics a "human endeavour" because the development of our understanding of the physical environment is the result of interactions between human minds and nature.

It is perhaps most important in the world of today, a world in which there is an "information explosion", to seek a broad understanding of the ways in which information is obtained, and the limitations, applications and implications of such knowledge.

In order to achieve this understanding, we shall not only examine the physics of the twentieth century, but we shall study the evolution of scientific thought from the past to our contemporary point of view.

This examination can reveal to us one characteristic of the human mind that is particularly interesting. It is symbolized by the nine dots we have used as the basis for the simple puzzle below.



Draw the nine dots on a piece of paper

Join all nine dots by four straight lines without lifting your pencil from the page.

Try it!

If you have not succeeded yet, the answer is found on the back cover.

It is fun to watch a group of people attempt this problem. Invariably, most people draw lines in all directions, but stop when they reach the outside row of dots. They seem hemmed in by those outside dots as if they feel them representing some kind of boundary on the problem. In order to succeed, your pencil must break through this self-imposed boundary (there was nothing in the instructions to suggest such a boundary existed!) You may know other puzzles of this kind, or remember problems that you have solved only after breaking through some boundary on your thinking. We shall call such mental boundaries paradigms. Most people, faced with a problem, search for some familiar pattern or model on which to base their thinking. That is, consciously or unconsciously, they seek to establish a paradigm. We suggest that by examining some of the major paradigms that have existed in the past, and the ways in which they were broken, we can go a long way towards recognizing the paradigms of today, an important ability for success in the discipline of physics, or any other human endeavour. As the distinguished Canadian critic, Northrop Frye, has said "It is a part of the whole educational process to recognize as far as possible the extent of one's own conditioning and to try to go as far as humanly possible in becoming aware of what one's own assumptions and axioms are." (Northrop

Frye in an interview with Bruce Mickleburgh in "Monday Morning", Sept./72.)

Now let us make some specific comments on the structure of the course.

There are six units in all. Each has one or two central themes, and makes its own kind of contribution to your knowledge of physics.

Much of what happens in the universe involves *motion*, and it is important to be able to describe how and why objects move. These topics, called kinematics and dynamics, form the basis of the information in Unit 1.

Unit 2 is a further discussion of the laws of motion. We expand upon the concepts of simple motion by taking the laws out the limited sphere of the earth's gravity and applying them to the motions of our solar system and ultimately, the universe. As you will see the analogy to the dot problem applies. Man had to expand beyond the earth (the limits of the dots) into the universe (beyond the dots) to continue his search for knowledge. Where is man located in the vastness of space? Where are the stars? Is there an order to the Universe? The variety of answers to these questions, and the knowledge that the answers are still changing, is the concern of Unit 2. The development of man's sources of useful energy and the possibility of a 20th century energy crisis are also considered.

In the third unit the formulation of a few of the famous "Conservation Laws" is discussed with emphasis on the fascinating properties of momentum, energy, and the transformation of waves.

Unit 4 concentrates on the use of "models" in science, particularly focussing on the classic conflict between two rather successful models to describe the nature of light—the particle model proposed by Sir Isaac Newton, and the wave model championed by the Dutch physicist Christian Huygens. Although we shall see how this particular conflict was resolved, we shall also see how a similar problem about the nature of light still exists today.

The story of electricity, the relationship between electricity and magnetism, and the tremendous impact that developments in this field of physics has had on our way of life are traced in the fifth unit.

Finally, the world of the very small, the world of objects of atomic and nuclear sizes, the world of X-rays, gamma rays and radioactive particles, the world of nuclear fission, fusion, and atomic energy, is probed in Unit 6 .

Throughout the text, you will find questions at the end of most sections. These are usually straightforward questions which can be answered directly from the preceding material. They focus on the major points made in the section. Problems, graded into A and B levels of difficulty, are provided at the end of each chapter to help you develop further your ability and insight into the issues in the text. Many of the questions at the end of the sections and chapters are marked with an asterisk. These are questions of a discussion type and so the "answers" will not be found at the back of the book.

We believe that no student taking this course should limit his reading to this text alone. One of the habits a student must acquire is to pursue a given topic for several points of view. To this end, there are many references made throughout the text to books that have been read and enjoyed by other students studying physics at your level.

Finally, we should like to point out to you the importance of laboratory work. Ultimately, all science is guided by the phrase "theory guides, but experiment decides". Measuring properties of nature directly usually raises a host of difficulties that are not met when working through the same material with pencil and pad. Some whimsical scientists (original sources unknown by the authors), have given concise expression to feelings that any student of science can share from time to time in the forms of "*Murphy's Law*"—if anything can go wrong it will—and "Allen's *Axiom*"—when all else fails, read the instructions.

We hope that you don't find these applicable to yourself too often this year, but when you do, smile, re-organize, and try again!

The authors gratefully acknowledge their colleagues who have taken the time to read and criticize their manuscript. In addition, the authors acknowledge, with thanks, the co-operation received from their publisher, Holt, Rinehart and Winston of Canada Limited.

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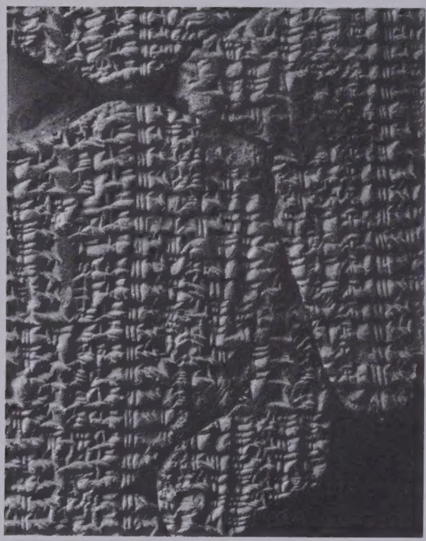
Prologue



The positions of Jupiter from 132 B.C. to 60 B.C. are recorded on this section of Babylonian clay tablets, now in the British Museum.

Astronomy, the oldest science, deals with objects which are now known to be very distant. Yet to you and me, as to the earliest observers of the skies, the sun, moon, planets, and stars do not seem to be far away. On a clear night they seem so close that we feel we can almost reach out and touch them.

The earliest astronomical observations, which each of us has made, are concerned with the sun and the moon: their rising in the east and setting in the west, the lengthening and shortening of daylight hours, the noontime altitude of the sun, the moon's phases, and perhaps, an eclipse. If we have been fortunate enough to view the night skies without the interference of smog and artificial lighting, our understanding of the ancient view is likely to be keener, for then we shall have seen the nightly westward progression of the constellations, the rising and setting of stars in our southern skies, and the near circular motion of those stars which are near the star Polaris. We may even have seen that different constellations become visible in our southern sky as the seasons change, and that the planets move against the background of the fixed distant stars. Whatever your experience has been, you will find that if you begin to keep simple records of your observations you will become more appreciative of the questions that arose in the minds of the ancients.

The lives of the ancient people, and indeed of nearly all people who lived before electric lighting, were dominated by heavenly events. The working day began when the sun rose and ended when the sun set. Human activity was dominated by the presence or absence of daylight and the sun's warmth, changing season by season.

Timekeeping is one of the primary functions of the *Dominion Astronomical Observatory* in Ottawa.

Clocks and calendars were devised to record the motions of the sun and moon in the sky. The recording of astronomical events is most important to a civilisation dependent upon agriculture, since the survival of the society depends upon knowing when to plant and harvest. The making and improvement of the calendar, tied as it was to seed-time and harvest, was often entrusted only to the priests, who consequently became the first astronomers.

Much later, man started to question the motions of the

objects in the sky. His early answers to his questions may be found in the mythology of early civilisations. Out of these early answers came an association between events on earth and those in the sky which developed into the study of astrology. Astrologers provided many observations that were later used in the science of astronomy. Although contemporary scientists are somewhat skeptical about astrology, many of the astronomers of the fifteenth and sixteenth centuries whom we shall study earned their living from casting horoscopes. In 1623 the astronomer Johannes Kepler cast a horoscope for Emperor Wallenstein with the prophecy that during March of 1634 dreadful disorders would descend upon the land.

The mythologies of the Egyptians, Greeks, Romans, Mayans, and Aztecs are based upon the deification of astronomical objects.

Wallenstein was murdered February 25, 1634.

The removal of the gods from the observable heavens as an explanation for celestial phenomena was an important step in the evolution of science. The early Greeks searched for simple explanations and their theories became the basis of early astronomy. Their geocentric view of the universe dominated western man's thinking for almost two thousand years. These views will form the starting point for our study of man's changing view of the universe. We shall follow the evolution of the universal model, from the ancient Greeks' view to our own, sharing in the frustrations and successes of the astronomers who attempted to find explanations that could be fitted to their observed data.

geocentric—earth-centered

It is important to notice, as you work your way through this unit, that the reasons for a discovery are often as significant as the discovery itself. Men, who believed that the answers to many of life's mysteries could be found in the stars, were searching for more than the structure of the universe. Take time to consider the social structure of each period studied. In this way you can understand the evolution of physics. Respect the ancient astronomers for their accomplishments. For as you sit and look at the night sky, is it not obvious that the earth is at rest and that the celestial sphere containing the stars is rotating westward about us? Appreciate, also, the scientists who challenged this structure by saying "No, it is not obvious".

Stonehenge, England, apparently a prehistoric observatory.

Chapter 6 *Where is the Earth?*

Where is the Earth?

Chapter Six

6.1 The Motions of the Stars

After observing the night sky for many evenings over a period of many years, the following observations might be made:

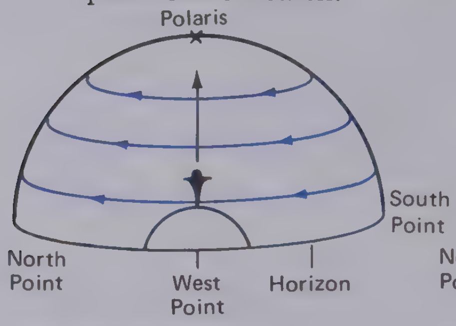
1. The stars appear not to move relative to one another, and consequently the constellations have almost the same shape now as they had many years ago.
2. Different constellations become visible in our southern sky as the seasons change. Gemini, Orion, and Taurus are seen in the winter sky, whereas Sagittarius and Scorpio are seen in the summer months.
3. Each evening the entire *celestial sphere* appears to rotate westward at a rate of about 15 degrees per hour around a point very near to the star Polaris.

Your view of the nightly motion of the stars and of particular constellations against the celestial sphere is determined by your position on the earth. Standing at the North Pole of the earth, the star Polaris is found directly overhead with the constellations rotating westward always in sight, neither rising nor setting. *Astronomers refer to the angle made by the line of sight of a star and the horizon as its* **altitude**. For an observer at the North Pole the altitude of Polaris is 90 degrees. Each of the other stars, visible from the North Pole, remains at a constant altitude as it progresses westward. An observer at the North Pole is able to see only half of the stars on the celestial sphere. An observer located at the South Pole is able to see the other half.

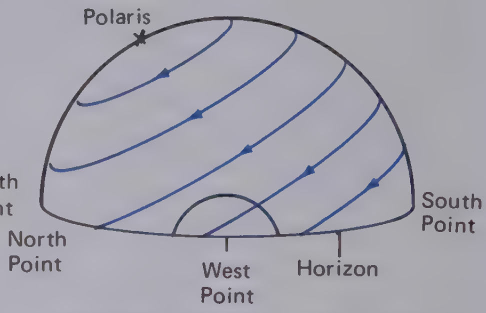
Consider now an observer on the equator. His view is quite different. The star Polaris is located at the far north of his horizon, with an altitude of 0 degrees. In the course of an evening he observes stars rising in the west, travelling westward at a rate of 15 degrees per hour and then setting in the west. For this observer all the stars are located above and below his horizon for equal periods of time. All the stars on the celestial sphere can be viewed from his position.

The motions of these bodies are not difficult to observe—you should make a point of doing so. Suggestions are given in the laboratory guide.

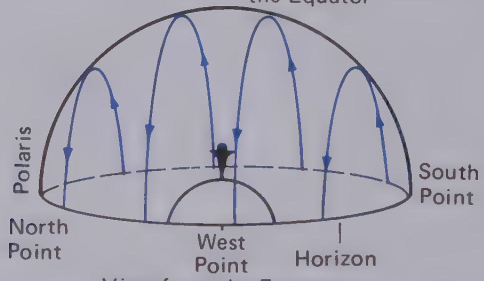
Daily stellar motions as seen by observer at different positions on earth.



View from the North Pole

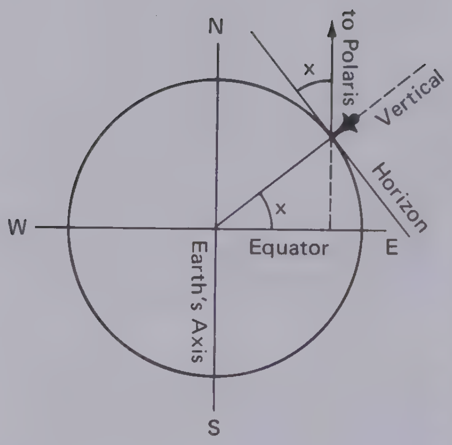


View from between the North Pole and the Equator



View from the Equator

Try some naked eye Astronomy, pg. 91.



This diagram shows that the altitude of Polaris equals the latitude of an observer. The angles marked are equal. Can you see why this is true?

Celestial sphere; An imaginary sphere on the inner surface of which the heavenly bodies appear to move.

An observer located somewhere between the North Pole and the equator makes the following observations. The altitude of the pole star depends upon the observer's latitude on the surface of the earth. One is able to show by simple geometry *that the altitude of Polaris equals the latitude of the observer.* Early navigators sailing across large bodies of water used this geometric principle to maintain a fixed latitude on the surface of the earth. For this observer, the stars in the northern sky appear to rotate counter-clockwise about the pole star. The stars in the southern sky seem to rise in the east and set in the west much like those which can be seen from the equator. The stars near Polaris in the northern direction are always above the horizon. All the other stars are visible for different periods of time depending upon the observer's latitude and the star's position on the *celestial sphere.* You can become familiar with this daily motion of the stars on the celestial sphere by examining the diagrams and photos in the margins of this section and by using a celestial globe.

We observe different constellations in the southern sky during different seasons due to our inability to see stars when the sun is above our horizon. Thus to understand this difference we must examine the motion of the sun.

Q1 What is the latitude of your school? What is the altitude of Polaris from the school? Check your prediction.

Q2 If you are observing from a latitude of 50 degrees N, describe the nightly path of stars

a) in the northern sky, b) in the southern sky.

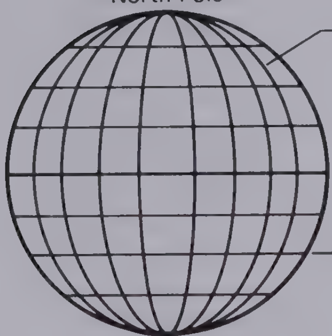
Q3 Describe the apparent motions of the stars as seen by an observer at the south pole.

See problem 6.1 on page 18.

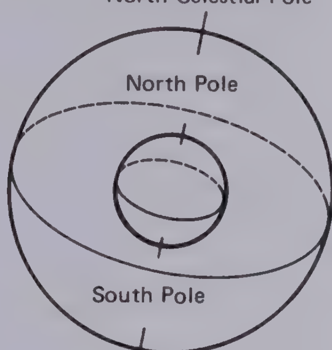
6.2 The Motions of the Sun

Before we examine the motion of the sun, we must first establish a method of describing the position of objects on the celestial sphere. Let us compare this problem with one that is more familiar to us, namely, describing the position of an object on the surface of the earth. The location of a point on the surface of the earth is defined by two angles called the latitude and the longitude. The *latitude* of a place on the surface of the earth is defined as its angular measure from the equator along the *meridian* of the place. It is measured in degrees, north or south of the equator. In order to measure longitude we must establish an origin or zero point from which to measure. Such a zero line was established at the meridian which passes through Greenwich, England. *Longitude* is thus defined as the angular measure along the equator between the meridian of Greenwich and the meridian of the place in question. The terms latitude and longitude and their use are probably familiar to you from your studies in geography. From your work with maps you know that cartographers in their maps of the earth show the earth as though it were flat and that this mapping procedure causes some distortion.

See Experiment 6.2, *Motions of the Sun*, pg. 94.

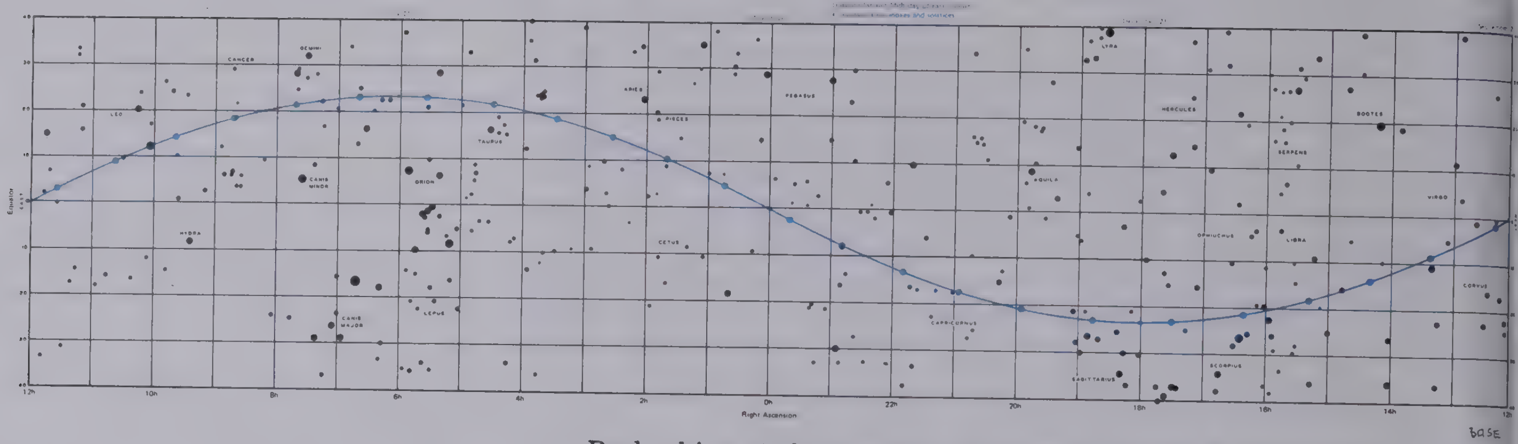


The Earth



Drawing a map of the sky with a coordinate system for determining the position of celestial objects is very similar to mapping the earth. We can, by using points on the earth, set up some reference points on the celestial sphere. *The point directly above the North Pole of the earth near the star Polaris is called the* **North Celestial Pole.** Similarly a point directly above the South Pole of the earth is called the **South Celestial Pole.** By projecting the equator of the earth out onto the celestial sphere, a line running completely around the celestial sphere midway between the North Celestial Pole and the South Celestial Pole is obtained. This line is called the **Celestial Equator.** The celestial sphere can be illustrated either by showing the sky as a sphere or, as map makers often portray the earth, by showing the sky as a flat surface. **Declination** *can be defined as the angular measure of an object north or south of the celestial equator.* Now we have a frame of reference on which to describe a map of the yearly path of the sun as it appears to move across the sky.

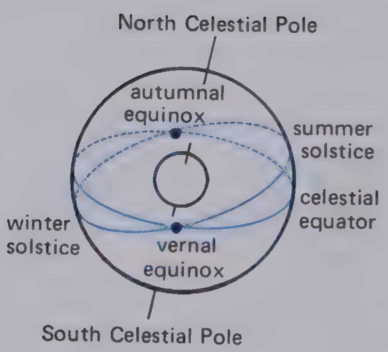
The Sun's Apparent Annual Motion—1972



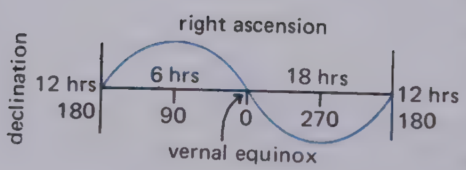
By looking at the diagram above and following the motion of the sun, the following observations may be made:

1. The sun appears to travel eastward around the entire celestial sphere each year, at a rate of about one degree per day.
2. The sun spends about half the year in the region of the sky north of the equator and the other half south of the equator. This variation in the declination of the sun accounts for the variation in the length of the day, the altitude of the sun in the sky, and the annual changes, which we call the seasons.

In addition to the yearly motion of the sun, there is also daily motion westward across the sky as the sun rises in the east and travels to the west. This daily motion westward at 15 degrees per hour is constant for all stars. Thus the sun may be thought of as travelling westward each day with the other stars, but slipping behind (eastward) 1 degree each day.



We should now define some terms that are an important aid in describing the sun's annual motion. *The sun's apparent annual path against the celestial sphere is called the* **ecliptic**. (The ecliptic is a great circle like the celestial equator.) The ecliptic is divided by four equidistant points: the two points of intersection with the celestial equator, and the two points where the two great circles are farthest apart. As the sun travels north, it crosses the celestial equator, about March 21, at the point called the **vernal equinox.** It continues on to its northernmost point, the **summer solstice**, about June 22, then turns south recrossing the celestial equator, about September 23, at the **autumnal equinox**, and continuing to its southernmost point, the **winter solstice**, about December 22 where it once more turns north.

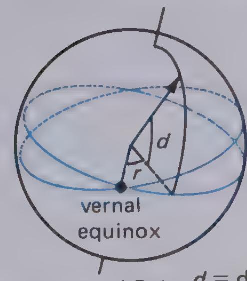


The great circle that serves the same purpose as the Greenwich meridian does in measuring terrestrial longitude, is the one which passes through the vernal equinox and the North Celestial Pole. *Measurement is made eastward along the celestial equator from the vernal equinox and is called* **right ascension.** Right ascension is measured in hours. (1 hour = 15°; 24 hours = 360°.) Thus a star's position may be given by the two coordinates, *right ascension* measured east from the vernal equinox along the celestial equator, always positive and less than 24 hours (360 degrees) and *declination* measured north or south of the

See Experiment 6.3, *The Celestial Sphere, the Equator Coordinate System,* pg. 99.

celestial equator, positive or negative, ranging from 0 degrees at the equator to positive or negative 90 degrees at the poles.

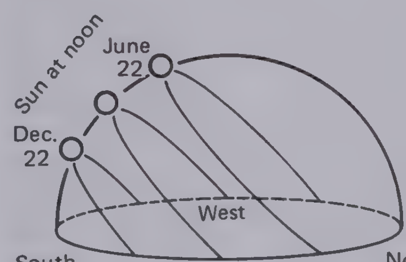
With our knowledge of the sun's motions and using the terms just defined, we are able to explain the existence of the seasons and observable variations in the constellations. Look at the chart and determine the approximate position of the sun on December 20. The sun's right ascension on this date is about 270 degrees. (Remember to measure right ascension eastward on the celestial sphere.) Recall that each day the entire celestial sphere rotates westward at a rate of 15 degrees per hour. The stars to the west of the sun rise before the sun and are in the sky at night. Those stars located to the east of the sun do not rise until after sunrise and are above the horizon during the day. These stars pass unseen across the sky. Thus the position of the sun on the ecliptic determines which constellations will be visible in the night sky.



d = declination
r = right ascension

We might summarize our discussion of the sun by saying it has three apparent motions:

1. Daily motion westward around the celestial sphere causing day and night.
2. Yearly drift eastward among the stars permitting us to see different constellations each season in the southern sky.
3. Yearly oscillation in declination affecting the length of day and the altitude of the sun and thereby causing the different seasons.



Duration of sunlight and altitude of sun determine seasonal variations in temperature. The diagram is for an observer in the northern latitudes.

Q4 Use the constellation chart on page 4 to determine the right ascension and declination of the sun on June 20, November 10, December 20, and March 21.
Q5 What constellation appears opposite the sun on December 20? How long after the sun passes does this constellation move overhead?
Q6 Will a star which rose at the same time as the sun today rise before or after the sun tomorrow?
Q7 What is the annual variation in declination of the sun?
See also problems 6.2 to 6.6 on page 18.

6.3 The Motions of the Moon

> Which is more useful, the sun or the moon? The moon, because it gives us light at night when it is dark. The sun shines in daytime when it is bright anyway. George Gamow.

George Gamow is the author of several popular books on science and is as well a famous theoretical physicist.

The moon shares the general east-to-west daily motion of the sun and stars. However, the moon slips eastward against the background of the stars faster than the sun does. Each night the moon rises nearly an hour later. When the moon rises in the east at sunset (opposite the sun in the sky), it is bright and shows a full disc (full moon). Each day thereafter, it rises later and appears less round, waning finally to a thin crescent low in the dawn sky. After about fourteen days, when the moon is passing near the sun in the sky and rising with it, we cannot see the

See Experiment 6.4, *Motions of the Moon*, pg. 103.

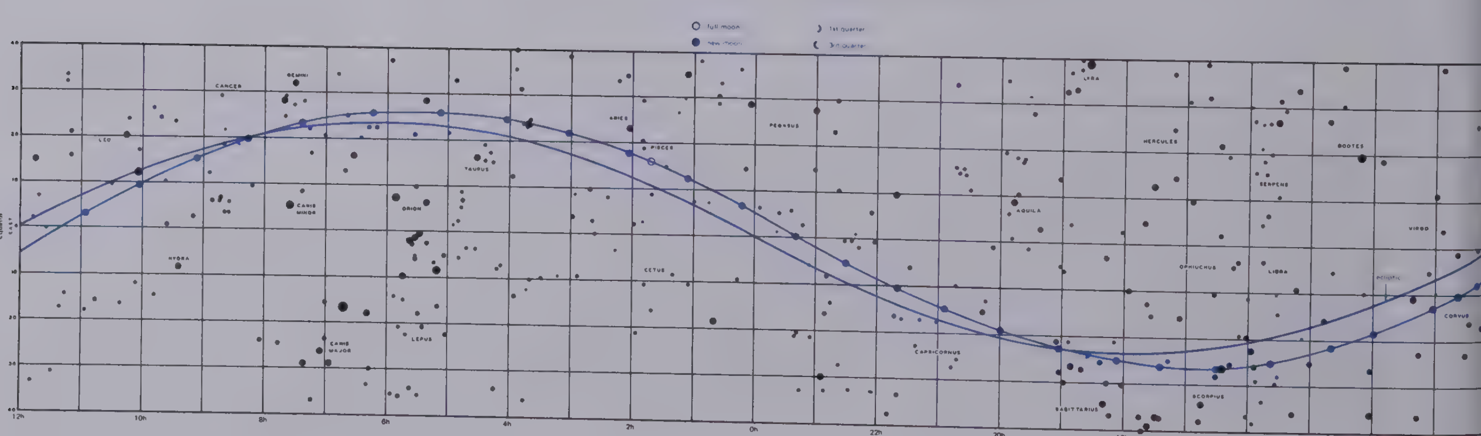
moon at all (new moon). After the new moon, we first see the moon as a thin crescent low in the western sky at sunset. As the moon rapidly moves farther eastward from the sun, the moon's crescent fattens to a half disc and then within another week goes on to full moon again. After each full moon, the cycle repeats.

As early as 380 B.C., the Greek philosopher, Plato recognized that the phases of the moon could be explained by thinking of the moon as a globe reflecting sunlight and moving around the earth in about 29 days. Because the moon appears so big and moves so rapidly compared to the stars, people in early times assumed the moon to be quite close to the earth.

The moon's path around the sky is close to the yearly path of the sun; that is, the moon is always near the ecliptic. However, the moon's path is tipped a bit with respect to the sun's path; if it were not, some interesting positions would result. The moon would come exactly in front of the sun at every new moon causing an eclipse of the sun; the moon would be exactly opposite the sun in the earth's shadow at every full moon, causing an eclipse of the moon.

The motions of the moon have been studied with great care for centuries, partly because of interest in predicting eclipses, and have been found to be very complicated. The precise prediction of the moon's position is an exacting test for any theory of motion in the heavens.

The Motion of the Moon for October 1972
(positions shown at one-day intervals)



*Q8 Draw a rough diagram to show the relative positions of the sun, earth, and moon during each of the moon's four phases.

Q9 If the sun has a right ascension of 6h (90 degrees) what is the right ascension of the moon if it is
a) a "new" moon? b) first quarter?
c) full moon? d) third quarter?

Q10 At what time of day are you likely to observe the moon in each of its phases?

Q11 Why do eclipses not occur each month?

See problem 6.7 on page 18.

*Questions marked with an asterisk are a discussion type and so the "answers" are not found at the back of the book.

6.4 The Motions of the Planets

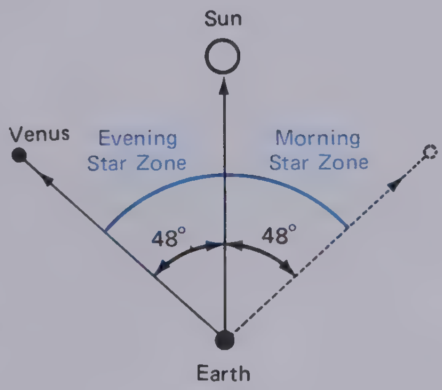
The motions of the sky objects discussed thus far appear to be very regular. However, if you observe the sky for many evenings you may notice that there are objects of significant brightness which move in irregular patterns. These wandering stars, called planets, were a source of questioning and theorizing for early astronomers. Five planets are visible without the aid of a telescope: Mercury, Venus, Mars, Jupiter, and Saturn. They appear in the sky near the region of the ecliptic.

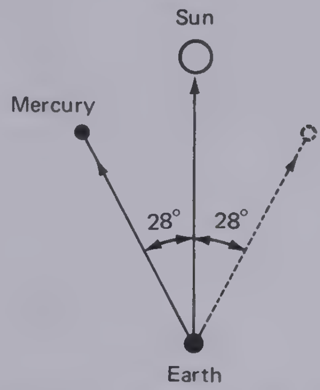
The planets, like the sun, moon, and stars, share in the daily westward motion of the celestial sphere; like the sun and the moon, they drift eastward against the background of the fixed stars. Confusion arises because the eastward motion is not regular. In fact, the planets seem to decrease speed eastward, stop, reverse westward, stop again, and then continue on their journey eastward. For Saturn, Jupiter, and Mars, this retrograde (backward) motion occurs in the region of the sky opposite the sun. However, the planets Mercury and Venus, which also exhibit retrograde motion, are never very far from the position of the sun in the sky. Mercury is confined to a zone of about 28 degrees, and Venus to a zone of 48 degrees to either side of the sun.

Not only do the motions of the planets pose a question, but so do changes in their brightness. During the summer of 1971, the planet Mars was observed in the southern sky, at its brightest; since then it has become a much fainter object. The planet Venus which appears as an early morning or early evening "star" also has regular changes in its brightness. Mercury may be observed as a morning star when it is west of the sun but it is more difficult to find than Venus.

In summary, the problems posed by the planets are:

1. How can we explain the irregularities of their motion?
2. Why do they exhibit variations in brightness?
3. Why do they seem to be confined to a region of the sky near the ecliptic?
4. Why are Venus and Mercury restricted to a zone of the sky near the sun while the other planets have no such restriction?

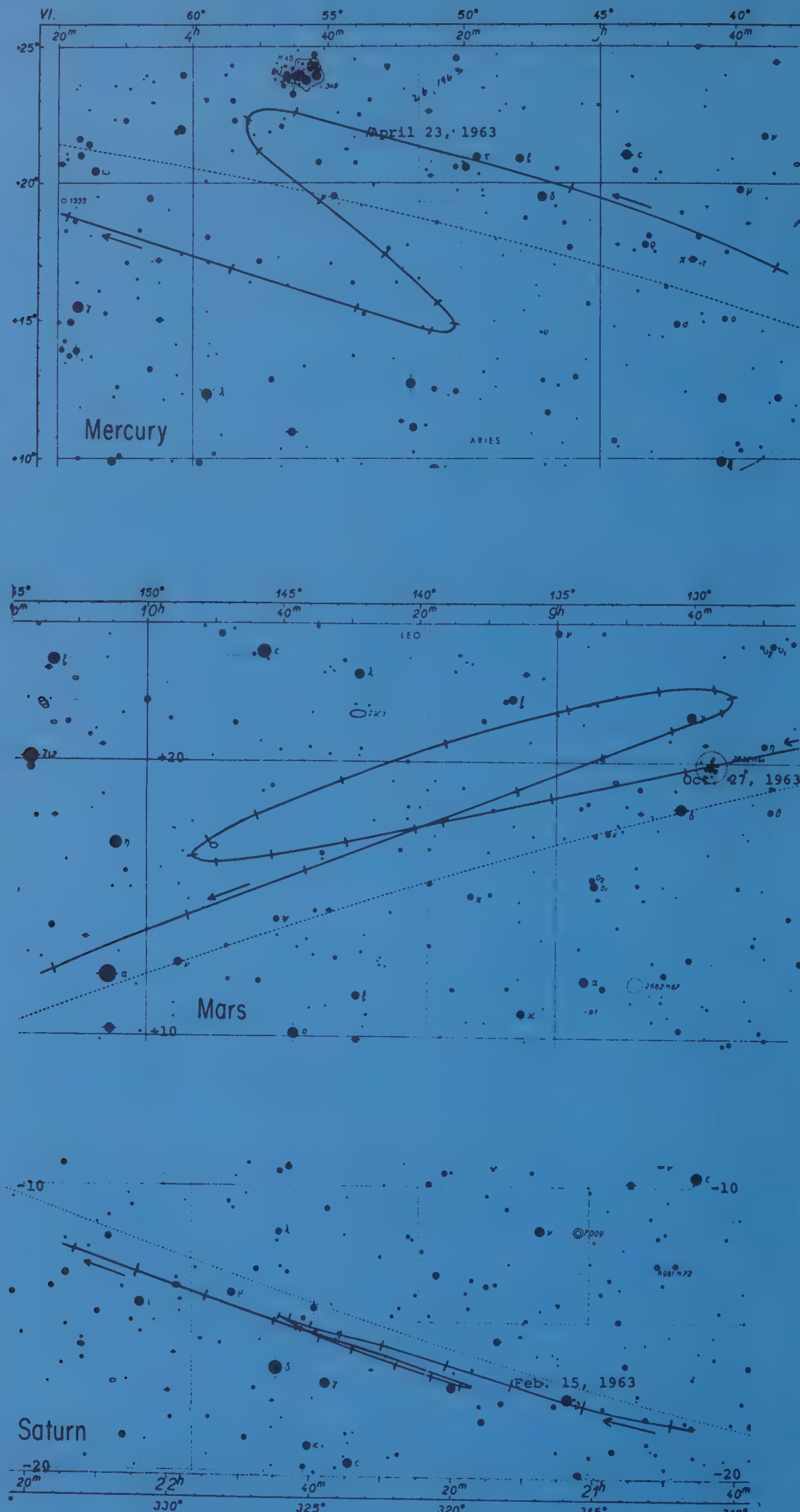




When the planets are at their maximum angle from the sun they are described as being at maximum elongation.

See Experiment 6.5, *The Planets,* pg. 105.

Retrograde motion of the planets Mercury, Mars, and Saturn in 1963



The retrograde motions of Mercury (marked at 5-day intervals), Mars (at 10-day intervals), and Saturn (at 20-day intervals) in 1963, plotted on a star chart. The dotted line is the annual path of the sun, called the ecliptic.

We shall now examine various solutions to these and other questions suggested in our discussion of celestial motion and shall see how the answers have changed over a period of about 2000 years.

Q12 Why are the planets Mercury and Venus never visible at midnight?
*Q13 Summarize Sections 5.2, 5.3, and 5.4 by comparing the similarities and the differences between the motions of the sun, the moon, and the planets.
Q14 An observer in Canada sights a bright object in his northern sky. Could it be a planet?

The Mythological Names of the Planets

Name	*Symbol*	*History*
Mercury	☿	The fastest and most elusive, because closest to the sun, Mercury is named for the fleet-footed, winged messenger god. Its morning appearance was called *Apollo.*
Venus	♀	Exceeded in brilliance by only the sun and the moon, Venus is named for the goddess of love and beauty.
Earth	⊕	Our planet was named for Mother Earth, a Greek deity.
Mars	♂	Dark and ruddy in colour, Mars is named for the god of war. Its two satellites are Phobos and Deimos, fear and panic.
Jupiter	♃	Three hundred and eighteen times the mass of the earth, the largest planet is named for the leader of the Roman gods.
Saturn	♄	The second largest planet is named for the Titan god of seed sowing, the father of Jupiter.
Uranus	♅	Near to the limit of naked eye visibility, Uranus was discovered in 1781 by William Herschel and named for the father of Saturn and therefore for the grandfather of Jupiter.
Neptune	♆	Found as a result of the mathematical calculations of Adams and Leverrier in 1845-46, Neptune is named for the god of the sea.
Pluto	♇	Found by accident in 1930 by examining photographs with the aid of a blink microscope, Pluto is named for the god of the underworld.

6.5 Summary of Terminology

Altitude: The altitude of a star is the angular measure of the star's position above the observer's horizon. ($0° \leq$ altitude $\leq 90°$.)
Polaris: The name of a star located almost directly above the earth's north pole. The altitude of Polaris equals the latitude of the observer.
Celestial Sphere: The imaginary sphere on the inner surface of which the heavenly bodies appear to be located.
North Celestial Pole: Point on the celestial sphere directly above the earth's north pole. (Almost at the position of Polaris.)
Celestial Equator: A line circling the celestial sphere midway between the north and south celestial poles. This great circle lies in the same plane (directly above) as the earth's equator.
Westward: The direction of the apparent daily motion of the objects on the celestial sphere.

Ecliptic: The sun's apparent annual path around the celestial sphere. (Each year the sun travels in a great circle eastward at a rate of about 1° each day.)

Vernal Equinox: The point where the sun crosses the celestial equator moving northward. This is the sun's position about March 21.
Right Ascension (R.A.): The first of two angular coordinates used to locate an object on the celestial sphere. This measurement is made eastward along the celestial equator from the vernal equinox. The angle is often measured in hours. ($1h = 15°$; $0h \leq$ R.A. $< 24h$.)
Declination (d): The second of two angular coordinates used to locate an object on the celestial sphere. The measurement is made north or south of the celestial equator. ($-90° \leq d \leq +90°$)
Summer Solstice: The location of the sun's most northerly position on the ecliptic. It occurs about June 22.
Autumnal Equinox: The point where the sun crosses the celestial equator moving southward. It occurs about Sept. 21.
Winter Solstice: The location of the sun's most southerly position on the ecliptic. It is reached about Dec. 21.
Retrograde Motion: A periodic reversal in the normal eastward motion of the planets across the celestial sphere. The planet appears to stop, travel westward, stop, and again continue on its eastward journey.

6.6 The Statement of the Problem

Science begins with a question. Since the beginning of time the heavens have silently posed many questions concerning the motions of celestial objects for anyone who would observe. Yet the people of ancient times were drawn to a study of the heavens not by clearly formulated questions but by the splendour of the night sky. An event must be recognized as posing a problem or

puzzle before a question can be formulated. However, remember that the way questions are asked reflects the contemporary state of science.

In the fourth century B.C., Greek philosophers asked a new question: How can we explain the cyclical changes observed in the sky? That is, what model can consistently and accurately account for all celestial motions? Plato sought a theory to account for what was seen, or, as he phrased it, "to save the appearances". The Greeks were among the first people to want to explain natural phenomena in ways that did not require the intervention of gods and other supernatural beings. Their attitude was an important step towards science as we know it today.

Other ancient civilizations developed their own views of the universe. We shall consider only the Greek view as an example of early astronomical thought.

The approach taken by the Greeks and their intellectual followers for many centuries was already implied in a statement by Plato in the fourth century B.C. He defined the problem to his students in this way: the stars, representing eternal, divine, unchanging beings, move at a uniform speed around the earth, as we observe, in that most regular and perfect of all paths, the endless circle. But a few celestial objects, namely the sun, moon, and planets, wander across the sky and trace out complex paths, including even retrograde motions. Yet, being heavenly bodies, surely they too must really move in a way that suits their exalted status. Their motions, if not in a perfect circle, must therefore be in some combination of perfect circles.

Aztec Calendar Stone

What combinations of circular motions at uniform speed about the earth can account for the peculiar variations in the overall regular motions in the sky?

Notice that the problem is concerned only with the changing *apparent* positions of the sun, moon, and planets. These objects appear to be only points of light moving against the background of stars. From two observations at different times we obtain a rate of motion: a value of so many degrees per day. The problem then is to find a "mechanism", some combination of motions, that will reproduce the observed angular motions and lead to predictions which agree with observations. The ancient astronomers had no observational evidence about the distances of the planets from the earth; all they had were directions, dates, and rates of angular motion. Although changes in brightness of the planets were known to be related to their positions relative to the sun, these changes in brightness were not included in Plato's problem.

Plato's problem in explaining the motion of planets remained the most significant problem for theoretical astronomers for nearly two thousand years. To appreciate the later efforts and consequences of the different interpretations developed by Kepler, Galileo, and Newton, we shall first examine the solutions to Plato's problems as they were developed by the Greeks. Let us confess right away that for their time these solutions were useful, ingenious, and indeed beautiful.

Q15 What is meant by the statement that " . . . the problem is concerned only with the *apparent* positions of the sun, moon, and planets"?

*Q16 Describe briefly Plato's statement of the problem of describing the motion of the planets. How did the era in which he lived affect the way in which he asked this question?

6.7 The Early Greek View of the Universe

Simplicity and agreement with measured data are two criteria with which the scientist approaches his task of "explaining" physical phenomena. He attempts to build a physical or mathematical structure which behaves exactly as his data indicates. The simpler the model is, the more elegant and pleasing. Yet there are two sources of error in this process: the hidden assumptions and the data themselves. Plato assumed that the heavenly bodies must move in circular orbits simply because of the elegance and "perfection" of the circle. Aristotle largely ignored detailed measurement, and others were satisfied with obvious errors. Each model is more or less useful in the continuing progress of science, however, as it helps in the identification of hidden assumptions and exposes data to critical analysis. Thus the Greek models, initially simple and elegant were often modified and ultimately discarded in the search for greater accuracy and simplicity.

The early model suggested by Plato positioned the solid unmoving earth at the centre of the system. Many early Greeks probably regarded the earth as flat, but they later thought of it as a spherical object. Their arguments for this concept included the following:

1. A sphere is symmetrically perfect.
2. When ships travel from port they disappear over the horizon, much like going around the edge of a sphere.
3. During an eclipse of the moon, the earth's shadow is always circular.
4. When one travels north or south on the surface of the earth, the altitudes of the stars seem to change.

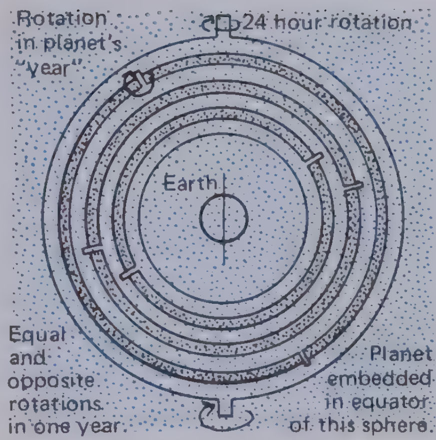
The annual north-south (seasonal) motion of the sun was explained by having the sun on a sphere whose axis was tilted 23½ degrees from the axis of the eternal sphere of the stars.

Surrounding the earth was a large sphere on which were located the fixed stars. This sphere was thought to rotate daily westward carrying with it the constellations and most of the objects that could be seen in the sky. The sun, moon, and planets which exhibit motions different from the fixed stars were somewhat more difficult to explain.

Plato's solution to the problem of different motions was based on the period which the moon, sun, and the visible planets took to orbit the earth. He suggested that each object was positioned on its own transparent crystalline sphere with the earth in the centre. The longer the object took for revolution, the farther the object's sphere was from the earth. According to this theory, Saturn, which has the longest period of revolution, is situated the farthest away from the earth. Jupiter and Mars were situated outside the sphere of the sun along with Saturn. Then came the sun, Mercury, Venus, and the moon, each sphere situated closer

to the earth-centre. Plato left it to later Greeks to determine the mechanism by which these spheres might explain the observed phenomena.

The inability of Plato to fit his theory to actual observations might be more easily understood if we consider a fundamental of his philosophy. He believed that only a pale reflection of the ideal world could be perceived, and that the ideal should be the centre of study rather than an imperfect imitation. Much as a student of geometry sketches a circle to help him envision the true shape, so observations can give only a rough idea of the ideal universe. Plato believed that astronomers must use their minds rather than their eyes to determine what the true nature of universe really was.



PART OF EUDOXUS' SCHEME: FOUR SPHERES TO IMITATE THE MOTION OF A PLANET

The sketch shows machinery for one planet.
The outermost sphere spins once in twenty-four hours.
The next inner sphere rotates once in the planet's "year". The two innermost spheres spin with equal and opposite motions, once in our year, to produce the planet's epicyclical loops.

You may feel that Greek science was "bad science" because it was different from our own or less accurate. But you should understand from your study of this chapter that such a conclusion is not justified. The Greeks were just beginning the development of scientific theories and inevitably made assumptions that we now consider invalid. Their science was not "bad science", but in many ways it was a different kind of science from ours. And ours is not the last word, either. We must realize that to scientists 2000 years from now our efforts may seem strange and inept.

Even today's scientific theory does not and cannot account for every detail of each specific situation. Scientific concepts are idealizations which treat only selected aspects of observations rather than the totality of the raw data. Also, each period in history has its own limits on the range of human imagination. As you already have seen in Unit 1, important general concepts, such as force or acceleration, are specifically invented to help organize observations. They are not given to us in final form by some supernatural genius.

As you might expect, the history of science contains many examples in which certain factors overlooked by one researcher turn out later to be very important. But how would better systems for making predictions be developed without first trials? Theories are improved through tests and revisions, and sometimes are completely replaced by better ones.

*Q17 Was the theory of Plato based upon observation or intuition? Discuss briefly.

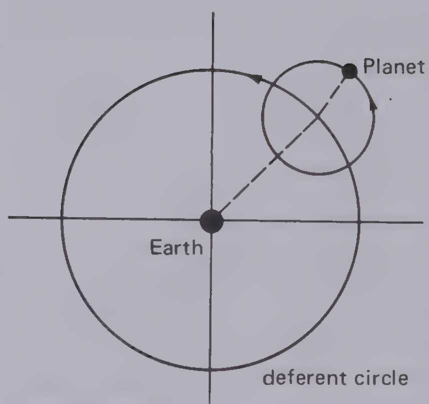
6.8 The Model of Ptolemy

One of the most significant attempts to modify this early model of Plato's in order to be able to predict the positions of celestial objects and hence establish some sort of astronomical handbook, was made by Ptolemy in about A.D.150. He set out to create a geometric model of the solar system that would permit the prediction of the positions of the celestial objects. His book, *Almagest*, was to re-emerge and form the basis for the study of astronomy in the fifteenth century.

Ptolemy's book, in Greek, was titled *The Great Composition.* The Arabic translation was called *Almagest-The Greatest-almjisti.*

Ptolemy modified the models of earlier Greeks and introduced some original ideas. His model situates the earth at the centre of the universe. The earth is massive, spherical, and unmoving. The stars are fixed on a large sphere which rotates westward once each day. The heavenly bodies, objects of perfection, must travel in perfect circles or combinations of circles. In order to satisfy this condition, yet account for the irregularities in the motions of the sun, moon, and planets, particularly the apparent retrograde motion of the planets, Ptolemy used geometrical methods which are most ingenious and complex. He used three principal geometric devices which we shall now examine: the epicycle, the eccentric, and the equant.

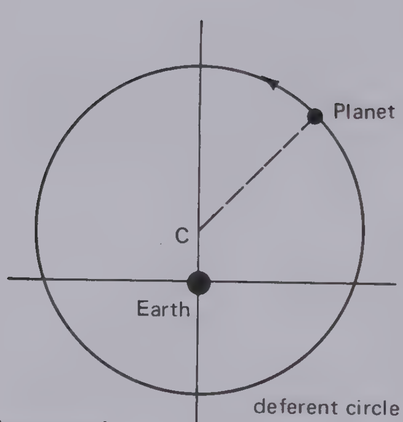
1. *Epicycle:* The epicycle was used by Greeks even before Ptolemy to account for the apparent retrograde motion of the planets. The path of a planet was considered to be the result of its simultaneous motion along two circles. According to this theory, the planets moved at a constant rate around the circumference of a small circle called the *epicycle.* The centre of this small circle in turn moved at a constant rate on the circumference of a larger circle called the deferent. Ptolemy found that by varying the radius of the epicycle and the angular speed of the planet on it, he could account fairly well for the retrograde motions of the planets.



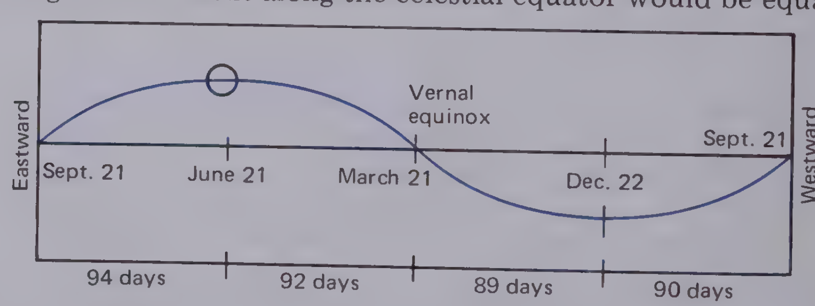
An epicycle

If a planet's speed on the epicycle were great enough, the planet would periodically appear to retrograde. In addition to explaining retrograde motion, the use of the epicycle allowed for changes in the planet's distance from the earth and hence accounted in some manner for the variations observed in the brightness of the planet.

2. *Eccentric:* The retrograde motion of the planets is the most obvious irregularity in celestial motion. A more subtle but easily observed irregularity is the rate of angular motion of the sun, moon, and planets as seen from the earth. This may be observed for the sun by considering the chart below. If the sun were moving uniformly on a circle around the earth, the times for each 90 degree movement along the celestial equator would be equal.

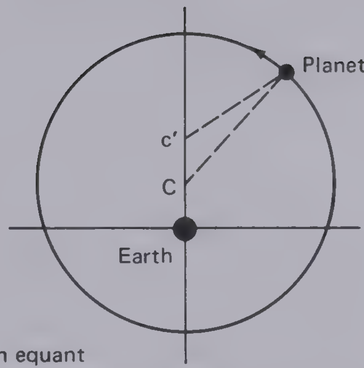


An eccentric

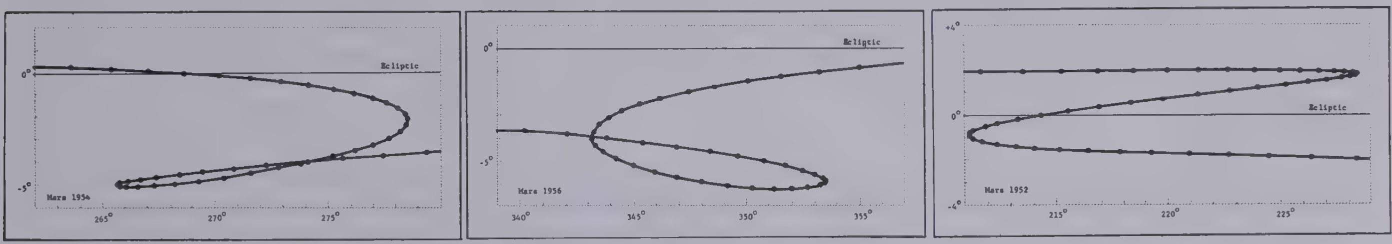


To satisfy the observed irregularity, Ptolemy used the *eccentric.* Although he considered the earth to be at the centre of the universe, he considered the centre of the deferent to be displaced from the earth. Then, a planet moving at a constant rate about this displaced centre would not appear to be in uniform angular motion as seen from the earth. Its angular velocity would be greatest when it was closest to the earth.

3. *Equant:* Even with combinations of eccentrics and epicycles, Ptolemy was not able to fit the motions of the five planets precisely. For example, as we see in the three figures below the retrograde motion of Mars is not always of the same angular size or duration. To allow for these variations, Ptolemy used a third geometrical device, called an *equant*, which is a modification of an eccentric. As shown in the margin, the earth is again off-centre from the geometric centre C of the deferent circle, but the motion along the circle is not uniform around C. Instead, it is uniform as seen from another point C', which is as far off-centre as the earth is, but on the other side of the centre.



An equant
C is the centre of the circle. The planet P moves at a uniform rate around the off-centre point C'. C' is called the equant.



Mars plotted at four-day intervals on three consecutive oppositions. Note the different sizes and shapes of the retrograde curves.

Q18 Ptolemy used the epicycle, eccentric, and equant to account for irregularities in the motion of the planets. Which irregularities does each explain?
Q19 What arguments did the Greeks use to suggest that the earth was spherical? Were these arguments "scientific"?

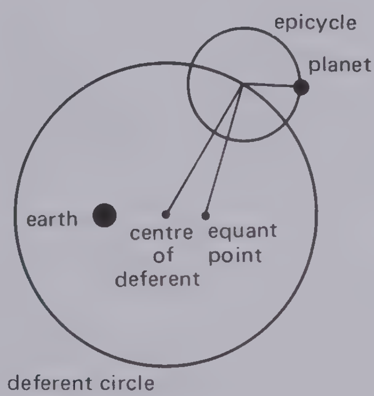
See also problem 6.10 on page 18.

6.9 Successes and Limitations of the Ptolemaic Model

Ptolemy's model always used a uniform rate of angular motion around some centre, and to that extent stayed close to the assumptions of Plato. But Ptolemy was willing to displace the centres of motion from the centre of the earth, as much as was necessary to fit the observations. By a combination of eccentrics, epicycles, and equants, he described the positions of each planet separately. For each planet, Ptolemy had found a combination of motions that predicted its observed positions over long periods of time to within about two degrees (roughly four diameters of the moon)—a considerable improvement over earlier systems.

The success of Ptolemy's model, especially the unexpected explanation of variation in brightness, might be taken as proof that objects in the sky actually moved on epicycles and deferents around off-centre points.

Of course, some difficulties remained. For example, to

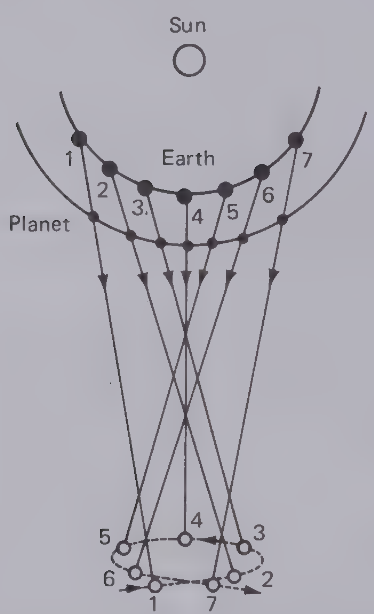


Ptolemy's scheme of motion.

explain the speed of the moon's motion, Ptolemy used such a large epicycle that during its orbit, the moon could be expected to change its apparent diameter by large amounts. Ptolemy surely knew that this was predicted by his model and that it does not happen in actual observation. But, his model was not intended to be "real", it was only a basis for computing positions.

Ptolemy was not content, however, with providing just a mathematical model. In a later book he proposed a mechanism to fit his earlier mathematical work.

The question that we might ask in retrospect is: "Didn't the Greeks ever query whether the earth might rotate or whether it might revolve around the sun?" There certainly are some advantages to an explanation of the solar system which has the sun as the stationary centre and the earth rotating once each day on its axis. These advantages were recognized by some Greeks, of whom we shall now consider briefly Aristarchus and the model he proposed in the third century B.C.



As the earth passes a planet in its orbit around the sun, the planet appears to move backward in the sky. The arrows show the sightlines toward the planet for the different numbered positions of the earth. The lower numbered circles indicate the resulting apparent positions of the planet against the background of distant stars.

Aristarchus proposed that the daily motions of the stars could be easily accounted for by considering the earth rotating eastward on its own axis once each day while the celestial sphere remained at rest. He also suggested that the sun was a great distance away from the earth and was probably much larger than the earth. Assuming this, Aristarchus further suggested that it would be more reasonable to have the earth revolving around the sun, arguing that this assumption would explain the retrograde motion observed in the planets as being due, not to an irregularity in the motion of the planets, but simply due to the planets being overtaken by the moving earth. The heliocentric hypothesis also explained the variation in the brightness of the planets. The planets located farther from the sun than from the earth would appear brighter during their retrograde motion because at that time they would be closest to the earth. The restrictions on the positions of Venus and Mercury to a region near the sun are explained by positioning them closer to the sun than to the earth.

Although the heliocentric model explained these phenomena more simply than the geocentric models proposed by the Greeks, it was rejected for several reasons. The first objection was that the heliocentric model contradicted the basic philosophical doctrine which placed the earth at the centre of the universe. Second, it contradicted common sense. If the earth were rotating, we would fly off, wouldn't we? We would certainly leave the clouds behind. We would constantly observe a rushing wind from the east. Third, if the earth were travelling around the sun, the direction in which we would have to look for any star, would be different when seen from different positions in the earth's orbit. This shift in the angle of the star had not been observed. Finally, Aristarchus did not develop his theory to the point of being able to predict the positions of the planets and hence his model seemed not to be of practical value. However, Aristarchus' ideas do illustrate that it is possible to break away from currently accepted theory and develop a completely new way of looking at a problem, and this is most important in our study of the evolution of science.

The name given later to this predicted shift in a star's position due to the position of the earth was *stellar parallax.*

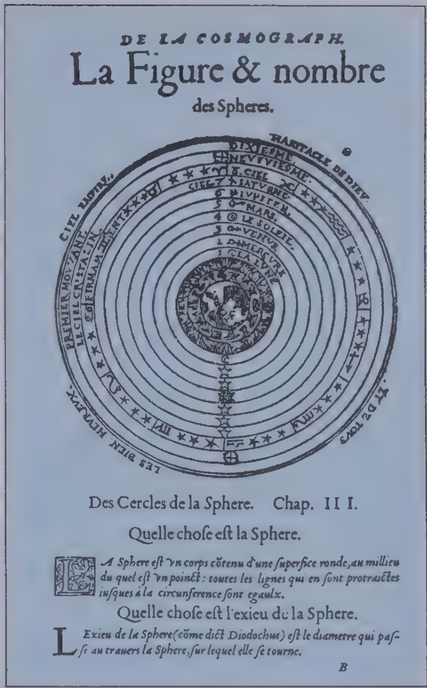
Thus the geocentric Ptolemaic model of the solar system proposed in 150 A.D. was used for about 1500 years by astronomers. There were some very good reasons for this long acceptance:

1. It predicted fairly accurately the positions of the sun, moon, and planets.
2. It explained why the fixed stars do not show an annual shift when observed with the naked eye.
3. It agreed in most details with the philosophical doctrines developed by the earlier Greeks, including the idea of "natural motion" and "natural place".
4. It had common-sense appeal to all who saw the sun, moon, planets, and stars moving around them.
5. It agreed with the comforting assumption that we live on an immovable earth at the centre of the universe.
6. Also, later, it fitted into Thomas Aquinas' widely accepted synthesis of Christian belief and Aristotelian physics.

Let us not judge the contribution to astronomy made by the Greeks as of little importance just becuase they proposed a scheme which is now regarded as incorrect. The Greeks built a firm foundation for the study of astronomy upon which future scientists could develop. They took the first step in changing man's view of the universe from the idea that the universe is controlled by the whim of the gods or created simply to serve man, to a realization that it is enormous and complex, but understandable. This realization was an achievement as great as any of the others that followed.

*Q20 What are the main successes and limitations of the Ptolemaic model?
*Q21 Why should students today study the astronomy of Ptolemy knowing it has been supplanted?
*Q22 How would the model proposed by Aristarchus explain the retrograde motions of the planets?

See also problems 6.11 and 6.12 on page 18.



DE LA COSMOGRAPH.

La Figure & nombre des Spheres.

Des Cercles de la Sphere. Chap. III.

Quelle chofe eft la Sphere.

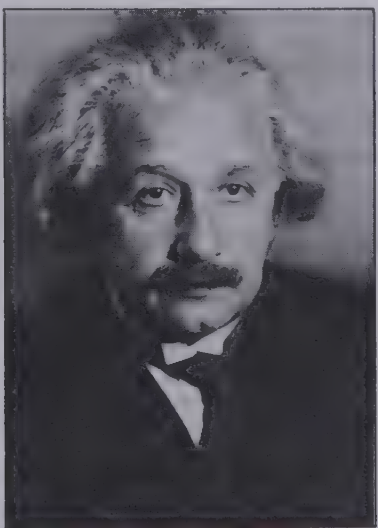
LA Sphere eft vn corps cōtenu d'une fuperfice ronde, au millieu du quel eft vn poinct : toutes les lignes qui en font protraictes iufques à la circunference font egaulx.

Quelle chofe eft l'exieu de la Sphere.

L'Exieu de la Sphere (cōme dict Diodochus) eft le diametre qui paffe au trauers la Sphere, fur lequel elle fe tourne.

B

A geocentric cosmological scheme. The earth is fixed at the centre of concentric rotating spheres. The sphere of the moon (lune) separates the terrestrial region (composed of concentric shells of the four elements Earth, Water, Air, and Fire) from the celestial region. In the latter are the concentric spheres carrying Mercury, Venus, Sun, Mars, Jupiter, Saturn, and the stars. To simplify the diagram, only one sphere is shown for each planet. (From the DeGolyer copy of Petrus Apianus' *Cosmographia,* 1551.)

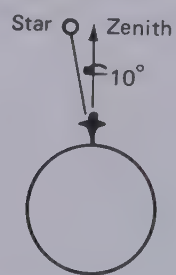


"The most incomprehensible thing about the world is that it is comprehensible."
Albert Einstein (1879-1955)

Problems Chapter 6

Section A

6.1 An astronomer on the planet Melblurb observes that a certain star passes directly over his observatory each night. However when he is visiting a friend who lives 500 lunks to the south he observes that the star now passes 10 degrees from his zenith. What is the circumference of Melblurb in lunks?



View from friend's house

6.2 Why can we see certain constellations only in the winter sky?

6.3 How could you determine your latitude on the surface of the earth in the northern hemisphere.

a) at night?
b) at noon?

6.4 What is the motion of the sun in degrees per hour across the sky?

6.5 What is the daily motion of the sun against the background of distant stars?

6.6 How could you use the shadow cast by a vertical stick on horizontal ground to find
a) the local noon?
b) which day was June 21st?
c) the length of a solar year?

6.7 What is the daily motion of the moon against the background of the fixed stars?

6.8 What is the meaning of each of the terms: equinox, summer solstice, right ascension, declination, ecliptic, celestial equator?

6.9 When it is 12 noon in Toronto, it is 9 a.m. in Vancouver. The distance from Toronto to Vancouver is 3350 km. From this information determine an approximate value for the circumference of the earth. (Why is it approximate?)

6.10 In Ptolemy's theory of the planetary motions there were, as in all theories, a number of assumptions. Which of the following did Ptolemy assume?
a) The vault of stars is spherical in form.
b) The earth has no motions.
c) The earth is spherical.
d) The earth is at the centre of the sphere of stars.
e) The size of the earth is extremely small compared to the distance to the stars.
f) Uniform angular motion along circles (even if measured from an off-centre point) is the only proper behaviour for celestial objects.

6.11 As far as the Greeks were concerned, and indeed as far as we are concerned, a reasonable argument can be made for either the geocentric or the heliocentric theory of the universe.
a) In what ways were both ideas successful?
b) In terms of Greek science, what are some advantages and disadvantages of each system?

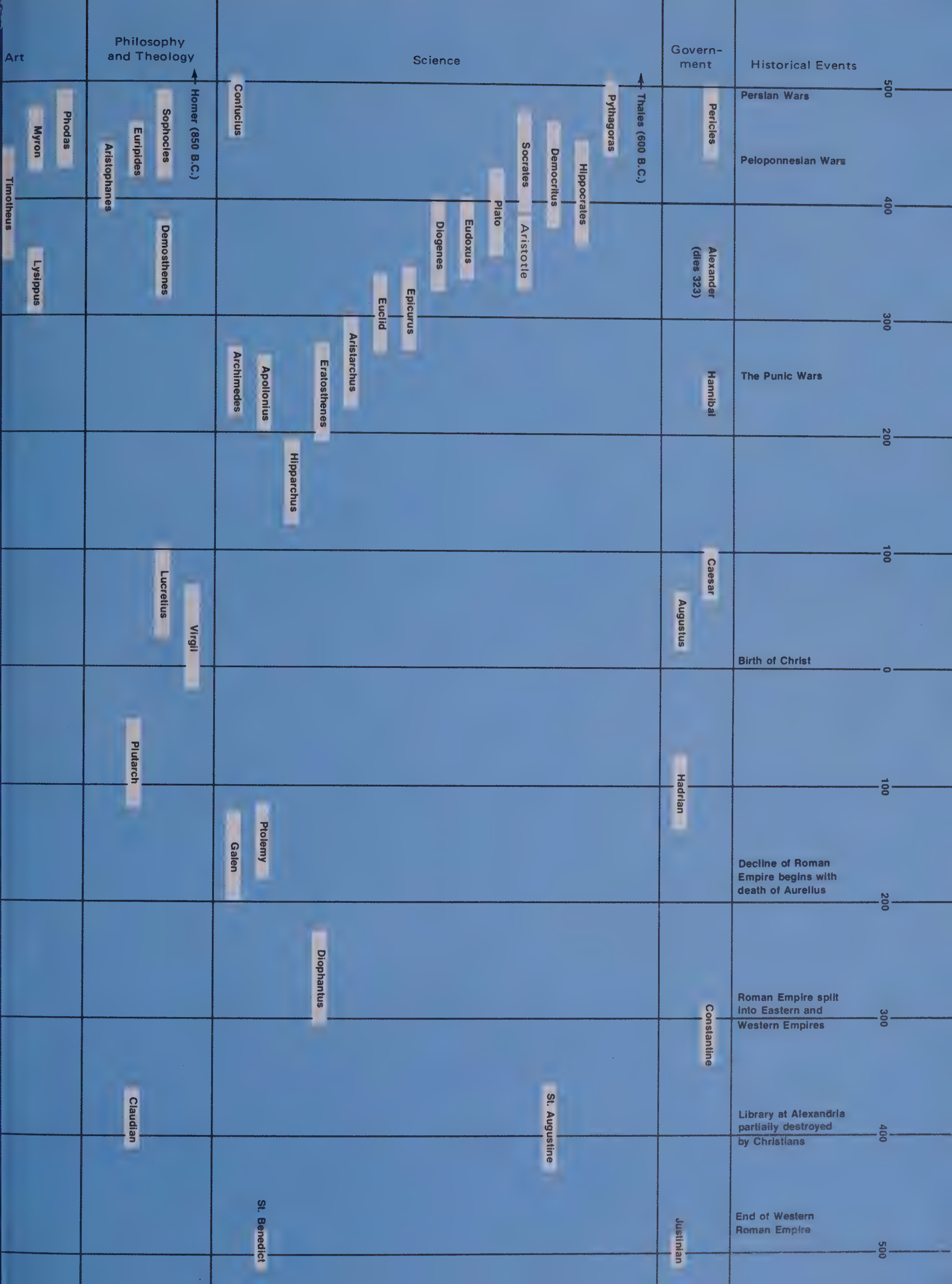
6.12 What were the major contributions of Ptolemy?

Section B

6.13 The latitude of an observer on the surface of the earth may be determined by sighting the altitude of the pole star. How would you determine your longitude? (You might like to read the article, "The Longitude" by Lloyd Brown in The World of Mathematics, Vol. 2, published by Simon and Schuster.)

6.14 It is possible to obtain a variety of orbits using the mathematical methods of Ptolemy. You might like to attempt the following. Draw an orbit so that
a) the planet moves on the epicycle with such a speed that it travels once around the epicycle in going half way round the deferent. The revolutions on the epicycle and deferent should be in the same direction.
b) the planet travels halfway around the deferent during the time it travels halfway around the epicycle. This time let the revolutions be in opposite directions.
If these diagrams are carefully drawn, you will observe that a regular orbit shape results having no retrograde motion. For retrograde motion, the planet must travel around the epicycle in a shorter time than the epicycle orbits around centre point.

6.15 Using the chart of annual motion of the sun found on page 4 suggest the position of the eccentric for the sun's orbit about the earth based on the model of Ptolemy.


Art
Philosophy and Theology
Science
Govern-ment
Historical Events
500
400
300
200
100
0
100
200
300
400
500
Phodas
Myron
Timotheus
Lysippus
Sophocles
Euripides
Aristophanes
Homer (850 B.C.)
Demosthenes
Lucretius
Virgil
Plutarch
Claudian
Confucius
Pythagoras
Thales (600 B.C.)
Socrates
Democritus
Hippocrates
Plato
Eudoxus
Diogenes
Aristotle
Epicurus
Euclid
Aristarchus
Eratosthenes
Apollonius
Archimedes
Hipparchus
Ptolemy
Galen
Diophantus
St. Augustine
St. Benedict
Pericles
Alexander (dies 323)
Hannibal
Caesar
Augustus
Hadrian
Constantine
Justinian
Persian Wars
Peloponnesian Wars
The Punic Wars
Birth of Christ
Decline of Roman Empire begins with death of Aurelius
Roman Empire split into Eastern and Western Empires
Library at Alexandria partially destroyed by Christians
End of Western Roman Empire

Chapter 7 *Does the Earth Move?*
The Work of Copernicus

Does the Earth Move? The Work of Copernicus

Chapter Seven

7.1 Nicolaus Copernicus: The Quiet Revolutionary

Nicolaus Copernicus was nineteen years old when Christopher Columbus discovered the New World. Because of the interest in navigation and discovery, and also the need of calendar reform, there was a resurgence of interest in the study of astronomy. Studying in Poland and Italy, Copernicus received degrees in law and medicine. However, most important to us in this work, was his study of the *Almagest*, Ptolemy's treatise on the motions and nature of heavenly bodies.

Suggested Reading

Angus Armitage, *The World of Copernicus* New York: Signet.

Thomas Kuhn, *The Copernican Revolution* New York: Random House.

Copernicus was dissatisfied with the Ptolemaic model of the universe as a basis for calculations of the positions of the planets. He disliked Ptolemy's use of different geometrical devices to satisfy the same observed phenomena. Although he accepted deferents, epicycles, and eccentrics, he could not justify the use of the equant. He could not accept this arbitrarily chosen point about which a planet travelled at constant rate. Copernicus saw the equant as a mathematical device which although it appeared to explain the observations had no physical reality and he considered it totally unacceptable.

In his words, taken from a short summary written about 1512

> . . . the planetary theories of Ptolemy and most other astronomers, although consistent with the numerical data, seemed likewise to present no small difficulty. For these theories were not adequate unless certain equants were also conceived; it then appeared that a planet moved with uniform velocity neither on its deferent nor about the centre of its epicycle. Hence a system of this sort seemed neither sufficiently absolute nor sufficiently pleasing to the mind. Having become aware of these defects, I often considered whether there could perhaps be found a more reasonable arrangement of circles, from which every apparent inequality would be derived and in which everything would move uniformly about its proper centre.

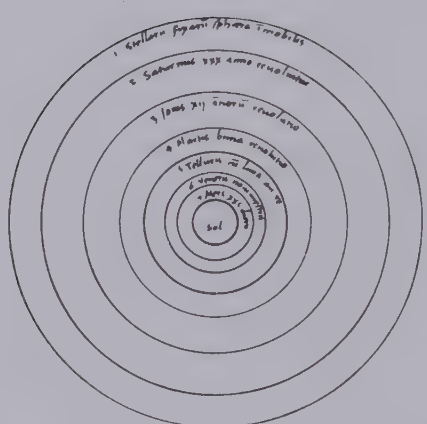
In about 1512, Copernicus developed the main ideas of a view of the universe that has come to be known as the

Copernican system. This new scheme was contained in a manuscript *The Commentariolus*, (*Little Commentary*), which received only limited circulation and was not published until 1878. *The Commentariolus* proposed a model of the universe which was fundamentally different from that stated in the Almagest. It set forth the following seven assumptions as basic axioms:

Copernicus continued the use of transparent celestial spheres in his model.

1. The heavenly bodies do not all move around the same centre.
2. The earth is not the centre of the universe, it is only the centre of the lunar sphere.
3. The centre of the motion of the planetary system, and hence the universe, is the sun.
4. The distance from the earth to the sun is negligibly small in comparison with the distance to the fixed stars.
5. The daily westward motion of the sky is due to the eastward rotation of the earth on its own axis.
6. The apparent annual motion of the sun against the fixed stars is caused by the earth's revolution about the sun. The earth therefore has more than one motion.
7. The retrograde motions of the planets are the result, not of their own motion, but of the earth's.

Copernicus included the earth's atmosphere as part of this eastward motion.



The above figure shows the main concentric spheres carrying the planets around the earth.

The motions of many objects in the sky were thus explained by the motions of the earth.

In *The Commentariolus*, Copernicus indicated that he would provide mathematical proofs and details in a later book. This major work, *De Revolutionibus Oribum Coelestium*, *On the Revolutions of the Spheres of the Universe*, was not published until 1543, the year of his death. One legend states that he first saw a copy of his printed work as he lay on his death bed. The book was written to parallel the arguments of the *Almagest*. The similarity in the format of these two works show the intensity with which Copernicus had studied the Greek text. The system Copernicus suggested was much more than simply a restatement of the heliocentric model of Aristarchus. *De Revolutionibus* was written on a mathematical foundation that permitted calculated predictions of the planetary positions. No predictions could be made from the model of Aristarchus.

By the publishing of *De Revolutionibus*, the stage was set for the "Copernican Revolution". However, this was not a revolution which swept rapidly across the geographical and mental barriers of mankind. Copernicus could not be portrayed as an active revolutionary. He had to be strongly urged to publish, and then agreed only towards the end of his life. In the following sections we shall briefly examine some of the merits and problems of the Copernican model to see why this was such a slow moving revolution.

*Q1 What reasons did Copernicus give for rejecting the use of the equant?

*Q2 Write a statement which Ptolemy might have made about each of Copernicus' seven statements.

7.2 Arguments for the Copernican System

The following arguments were prepared by Copernicus in anticipation of the criticism that was to follow the publication of *De Revolutionibus*:

1. Copernicus believed that his model was as philosophically and religiously sound as that of Ptolemy. By permitting the earth to revolve about the sun he had removed many of the irregularities from the heavens. Copernicus was able to eliminate the five larger epicycles Ptolemy needed to explain the retrograde motion of the planets. The apparent restriction of Mercury and Venus to a zone in the sky near the sun was simply explained by positioning the two planets in an orbit inside the earth's orbit. Copernicus believed this simplicity was more in keeping with the way a deity would design the heavens. This argument is much like that used by the followers of Plato in their attempt to determine what the perfect cosmos should be like.
2. To support his placing of the sun at the centre of the solar system, and hence the universe, Copernicus suggested that the sun is not like any of the other planets and yet Ptolemy, in his scheme of the planetary system, treated it as if it were. The importance of the sun as giver of light, warmth, and life can only be recognized by placing it in the unique central position of the universe. The feeling of Copernicus towards the sun is expressed in the following passage from *De Revolutionibus:*

> In the middle of all sits the sun enthroned. How could we place this luminary in any better position in this most beautiful temple from which to illuminate the whole at once? He is rightly called the Lamp, the Mind, the Ruler of the Universe . . . So the sun sits as upon a royal throne ruling his children the planets which circle around.

3. Copernicus knew that the daily motion of the sun, moon, and stars could be more simply described by a rotating earth. He answered criticism by suggesting that it is far simpler to consider an object the size of the earth rotating once a day than to consider the rotation of the entire celestial sphere. He countered the question, "Would not the earth fly apart if it were rotating?" by asking, "Would not the celestial sphere fly apart because it would have to rotate at a much faster speed?"
4. Copernicus did not use the equant in his geometrical calculations. Dissatisfaction with the equant was one of the initial reasons why Copernicus had not accepted the Ptolemaic model.
5. *De Revolutionibus* contained two important numerical calculations. First, it assigned a distance scale in the solar system. The distance from each of the five planets to the sun was calculated by Copernicus. The Ptolemaic model merely provided the position angles of the planets in the sky and did not consider a distance scale. The second values calculated by Copernicus were the periods of the planets about the sun. It is interesting to note how closely the values of Copernicus compare with our modern values.

CELESTIAL OBSERVATIONS

By PHILIP KISSAM, C. E.
Professor of Civil Engineering, Princeton University

I. The Principles upon which Celestial Observations are Based.

A. CONCEPTS.

1. The Celestial Sphere. To simplify the computations necessary for the determinations of the direction of the meridian, of latitude, and of longitude or time, certain concepts of the heavens have been generally adopted. They are the following:

a. The earth is stationary.

b. The heavenly bodies have been projected outward, along lines which extend from the center of the earth, to a sphere of infinite radius called the ***celestial sphere.***

The celestial sphere has the following characteristics:

a. Its center is at the center of the earth.

b. Its equator is on the projection of the earth's equator.

c. With respect to the earth, the celestial sphere rotates from east to west about a line which coincides with the earth's axis. Accordingly, the poles of the celestial sphere are at the prolongations of the earth's poles.

d. The speed of rotation of the celestial sphere is 360° 59.15′ per 24 hours.

e. With the important exception of bodies in the solar system, which change position slowly, all heavenly bodies remain practically fixed in their positions on the celestial sphere, never changing more than negligible amounts in 24 hours, and accordingly are often called *fixed stars.*

Celestial navigation involves comparing the apparent position of the sun (or star) with the "actual" position as given in a table called an "ephemeris".

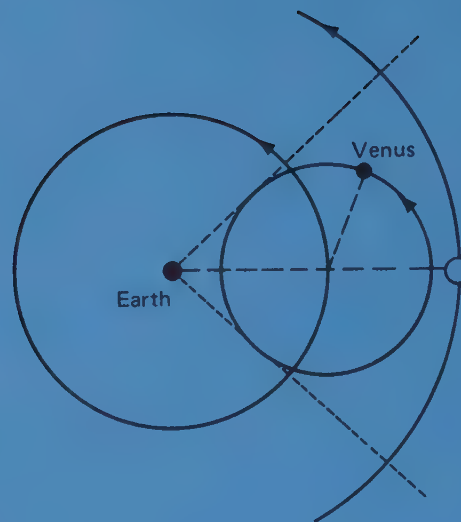
See Experiment 7.1, *The Shape of the Earth's Orbit,* pg. 115.

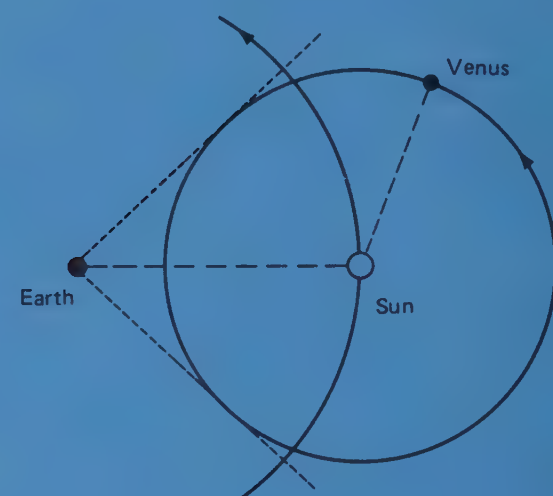
The change of viewpoint from Ptolemy's system to Copernicus' involved what today would be called a shift in the frame of reference. The apparent motion previously attributed to the deferent circles and epicycles was attributed by Copernicus to the earth's orbit and the planets' orbits around the sun.

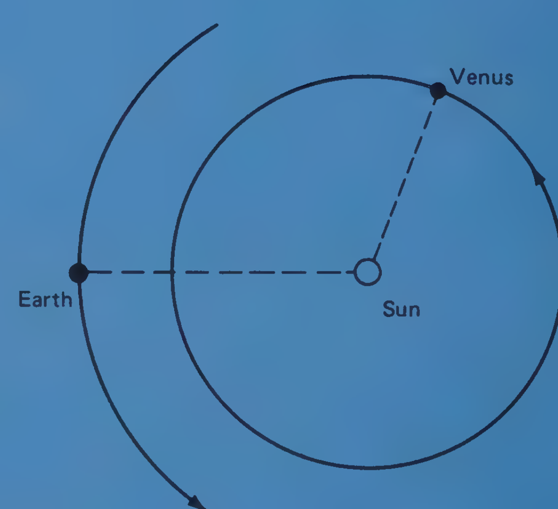
For example, consider the motion of Venus. In Ptolemy's earth-centered system the centre of Venus' epicycle was locked to the motion of the sun, as shown in the top diagram at the right. The size of Venus' deferent circle was thought to be smaller than the sun's, and the epicycle was thought to be entirely between the earth and sun. However, the observed motions to be explained by the system required only a certain *relative* size, as long as the epicycle was changed proportionally.

The first step towards a sun-centered system is taken by moving the centre of Venus' one-year deferent out to the sun and enlarging Venus' epicycle proportionally, as shown in the middle diagram at the left. Now the planet moves about the sun, while the sun moves about the earth. Tycho Brahe actually proposed such a system with all the observed planets moving about the sun which we will consider in the next chapter.

Copernicus went further and accounted for the relative motion of the earth and sun by considering the earth to be moving around the sun, instead of the sun moving about the earth. In the Copernican system, Venus' epicycle becomes its orbit around the sun and Venus' deferent is replaced by the earth's orbit around the sun, as shown in the botton diagram at the left. All three systems, Ptolemy's, Tycho's and Copernicus' explain the same observations. For the outer planets the argument is similar, but the roles of epicycle and deferent circle are reversed.

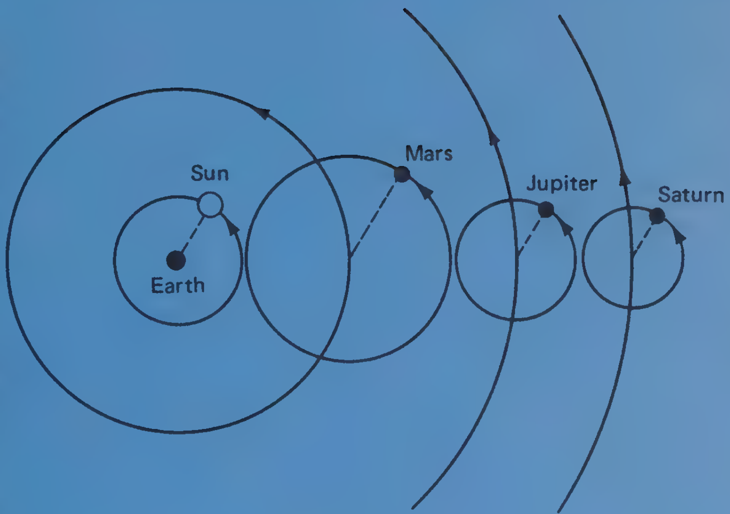


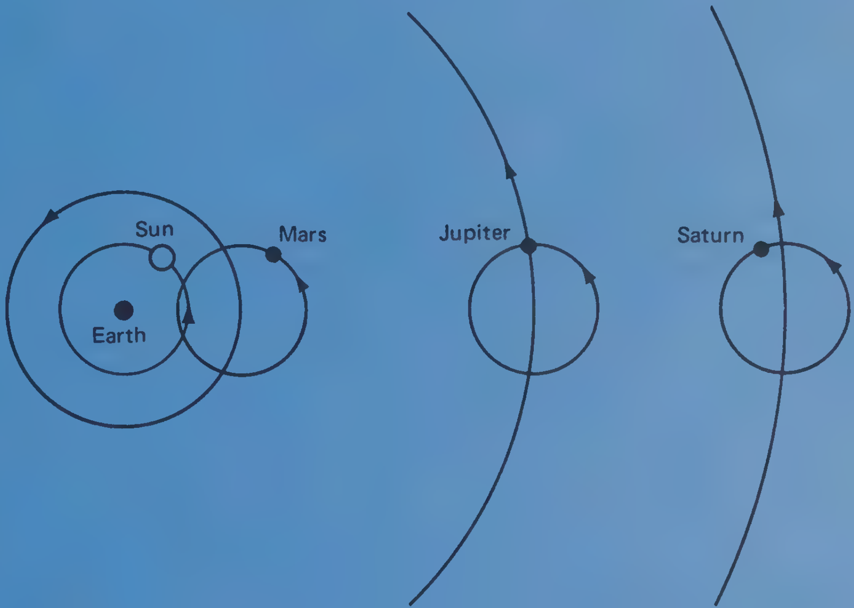


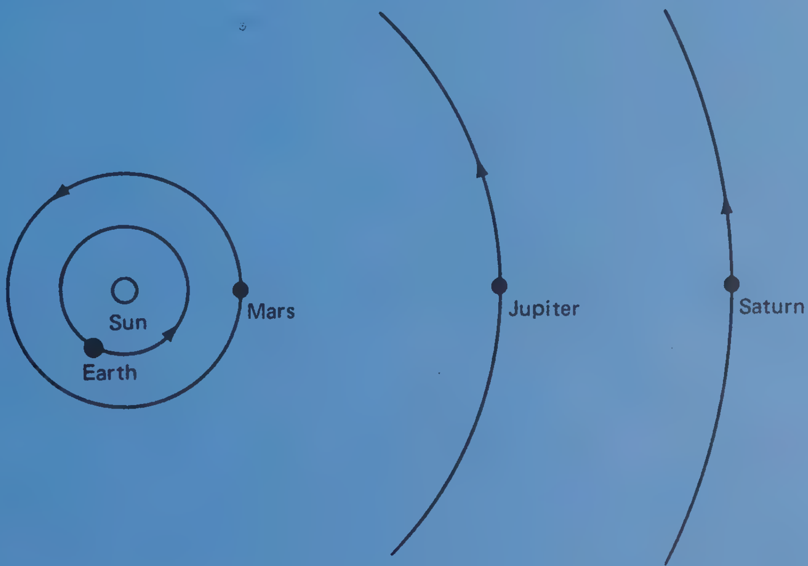


For the outer planets in the Ptolemaic system it was the epicycles instead of the deferent circles which had a one-year period and which were synchronized with the sun's orbit. The sizes of the deferents were chosen so that the epicycle of each planet would just miss the epicycles of the planets next-nearest and next-farthest from the sun. (This was a beautiful example of a simplifying assumption—it filled the space with no overlap and no gaps.) This system is represented in the top diagram at the right (in which the planets are shown in the unlikely condition of having their epicycle centres along a single line).

The first step in shifting to an earth-centered view was to adjust the sizes of the deferent circles, keeping the epicycles in proportion, until the one-year epicycles were the same size as the sun's one-year orbit. This adjustment is shown in the middle diagram at the right. Next, the sun's apparent, yearly motion around the earth is accounted for just as well by having the earth revolve around the sun. Also, the same orbit would account for the retrograde loops associated with all the outer planet's matched one-year epicycles. So all the synchronized epicycles of the outer planets and the sun's orbit are replaced by the *single* device of the earth's orbit around sun. This shift is shown in the bottom diagram at the right. The deferent circles of the outer planets became their orbits around the sun.







The average distance from the earth to the sun is called *1 astronomical unit* (AU).

PERIOD OF PLANETARY ORBITS

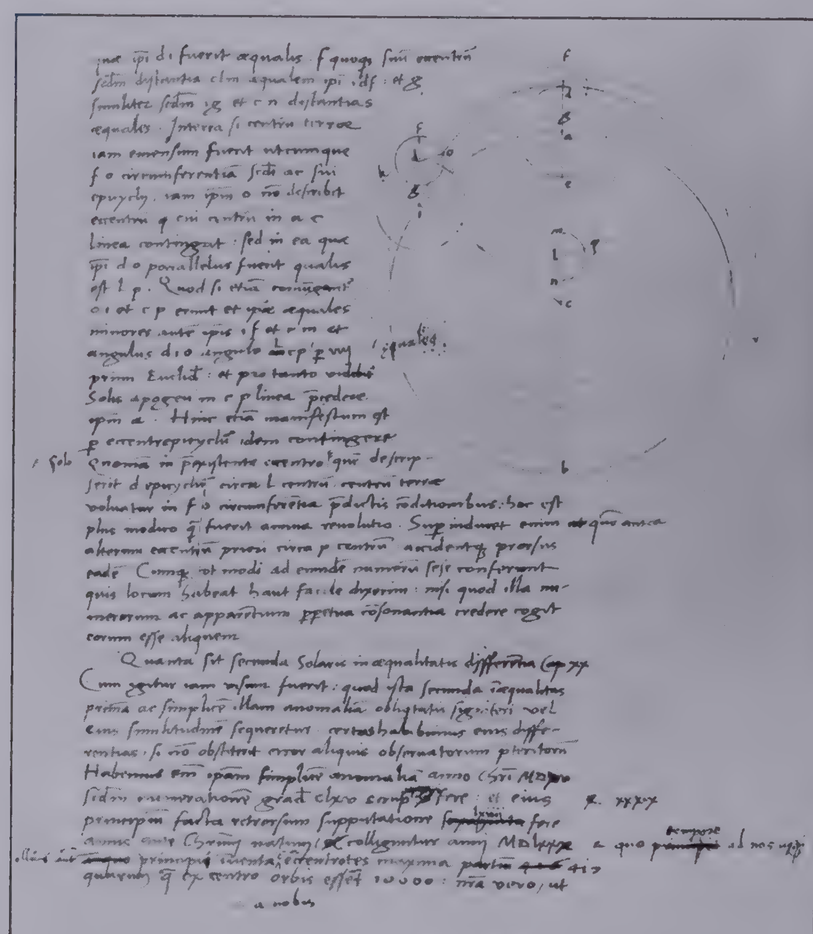
PLANET	COPERNICUS' VALUE	MODERN VALUE
Mercury	0.241 y (88 d)	87.97 d
Venus	0.614 y (224 d)	224.70 d
Mars	1.88 y (687 d)	686.98 d
Jupiter	11.8 y	11.86 y
Saturn	29.5 y	29.46 y

A method for determining the orbital radii of the inner planets is outlined in Activity 7.1, pg. 118.

RADII OF PLANETARY ORBITS

PLANET	COPERNICUS' VALUE	MODERN VALUE
Mercury	0.38 AU	0.39 AU
Venus	0.72	0.72
Earth	1.00	1.00
Mars	1.52	1.52
Jupiter	5.2	5.20
Saturn	9.2	9.54

***Q3** Consider each of the arguments for the system proposed by Copernicus and decide whether the argument suggested was made on scientific or religious grounds or to satisfy ordinary "common sense".



A page from Copernicus' manuscript *De Revolutionibus* showing detail of some of the epicycles in his model.

7.3 Arguments against the Copernican System

Students are often surprised that the Copernican model was not quickly accepted by scientists of the sixteenth century. Such surprise arises out of our twentieth century perspective. We have accepted our own model of the solar system for so long, that recognizing certain of its features in the Copernican model, we tend to label them "truth". Yet it is a measure of their growing need for "evidence" that the sixteenth century scientists raised the following arguments and were not quickly persuaded.

1. The Copernican system as presented in *De Revolutionibus* provided no computational advantages when compared to that of the Ptolemaic system. In order to satisfy the restriction that the motions of planets be of constant velocity on perfect circles, Copernicus was forced to introduce many spheres and epicycles. He accepted this restriction which was originally suggested by Plato. Copernicus, except for a few dozen measurements, used position tables in the *Almagest*. Many of these values were incorrect as a result of repeated copying and translation. The computations were neither more accurate nor simpler than those of Ptolemy.

2. In the Ptolemaic system *all* the objects of the solar system revolved around the earth. Many people thought this was much simpler than the Copernican system which placed the sun at centre of the planetary orbits but the earth at the centre of the moon's sphere. At the time Copernicus' idea was considered to cause a division between physics and cosmology. Moreover, experiments done with falling objects suggested that the earth was the physical centre of the universe. Copernicus wished to make the sun the cosmological centre. Copernicus justified having more than one centre about which heavenly bodies revolved by suggesting that "heaviness" was implanted in the sun, earth, and in all the bright planets.

Avoid the temptation of reading into Copernicus' use of the term *heaviness,* our modern meaning of the word *gravity.*

3. If the earth revolved around the sun, one should observe an apparent shift in the positions of the stars due to the earth's motion. This apparent motion of the stars is called *stellar parallax.* You can get some appreciation for this effect if you imagine yourself to be walking in a circle under the dome of a planetarium. As you move there is an apparent shift in the position of the stars you see overhead. This predicted parallax was not observed by astronomers. Copernicus suggested that this shift was very small and difficult to measure because of the immense distance of the stars.

This would also imply that no star could remain over the pole of the earth as the earth revolved about the sun. The star Polaris seems to contradict this.

4. In order to convince a scientist of the validity of a new theory, one must offer information which will support the theory. Copernicus could offer no such support. He could not show evidence to demonstrate either the revolution or the rotation of the earth. Common sense showed that the earth did not rotate and no evidence to convince people otherwise was provided. If stellar parallax had been observed, it would have demonstrated the revolution of the earth about the sun, but this parallax was not observed until after the production of large telescopes.

The first successful measurement of stellar parallax was made in 1838 by Frederick Bessel.

5. The heliocentric view of the universe was contrary to the teaching of Aristotle. As we have seen in Unit 1, the Aristotelian viewpoint had grown to great importance following the writings of Thomas Aquinas in the thirteenth century. Many teachers believed that if Aristotle's science were proved incorrect, it would shake the foundations of religious belief.

6. The Copernican theory was used as a basis for speculation on the possibility of the existence of life elsewhere in the universe. If the earth is removed from the unique central position of the universe, perhaps the uniqueness of man is also suspect. Could the other planets in the solar system or perhaps a planet near some other star in this immense universe be inhabited? This was a most awesome question in the sixteenth century. Giordano Bruno, a Copernican, who wrote a dialogue, *On the Infinite Universe and Worlds,* was burned at the staked for this and numerous other heretical suggestions in 1600.

You might like to read a discussion of Giordano Bruno in *Scientific American,* April, 1973.

*Q4 Consider each of the arguments against the system proposed by Copernicus and decide whether the argument suggested was made on scientific or religious grounds or to satisfy ordinary "common sense".

See problems 7.1 to 7.4 on page 29.

7.4 The Contribution of Copernicus

By means of *De Revolutionibus,* Copernicus made a clear mathematical statement of the heliocentric model of the solar system. He forced the scholars of the sixteenth century to become aware of the advantages of this system. They might reject it for many reasons, but they were forced to consider it. Many did not reject the Copernican theory but rather attempted to improve it and use it for the production of astronomical tables. Within one hundred years, the Copernican system was to gain acceptance by the majority of scholars. Then Copernicus was seen as the father of the astronomical revolution.

Sigmund Freud in 1920 included the following passage in *A General Introduction to Psycho-Analysis:*

> Humanity has in the course of time had to endure from the hands of science two great outrages upon its naive self-love. The first was when it realized that our earth was not the centre of the universe, but only a tiny speck in a world-system of a magnitude hardly conceivable; this is associated in our minds with the name of Copernicus . . .

The second blow was dealt by Charles Darwin in 1859 when *Origin of the Species* was published.

*Q5 In what way was the blow dealt by Copernicus to man's self-love similar to that dealt by Charles Darwin?

*Q6 How did the Copernican system encourage the suspicion that there might be life on objects other than the earth? Is such a possibility seriously considered today? What important kinds of questions would such a possibility raise?

Problems Chapter 7

Section A

7.1 Can you think of any examples where modern science conflicts with "common sense"?

*7.2 The term "a scientific argument" has a different meaning for the scientist of today than it had for the scientist of the sixteenth century. Discuss.

7.3 *Stop the World—I Want to Get Off*

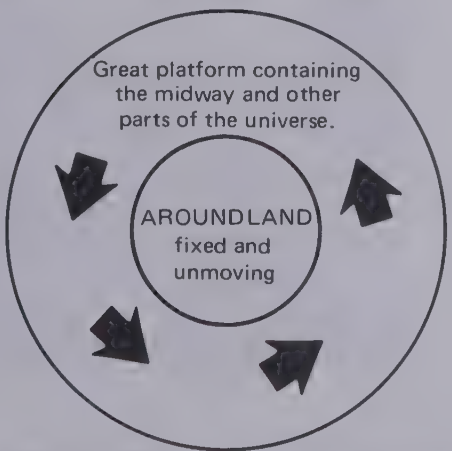
a) It is an interesting calculation to determine how fast someone at the equator is travelling due to the rotation of the earth. The radius of the earth is approximately 6,400 kilometres. This is the radius of the circle which points on the equator travel around every 24 hours. What is the speed of a point on the equator in kilometres per hour? Why does it not fly off?

b) Why is it an advantage to have rocket sites near the equator? In what direction should you launch the rocket?

c) You might also like to determine the speed of the earth as it travels around the sun.

7.4 This question is about a race of people who lived in Aroundland. Aroundland was located on a merry-go-round turntable in the centre of carnival midway. This turntable was in constant rotation, at a steady rate, in the clockwise direction. When one of the younger Aroundlandians asked his teacher why, when he looked out into the midway, everything was observed to be flying in a counterclockwise direction, his teacher replied with the following theory from a recently published textbook:

> "Aroundland is at the centre of the universe. It stands fixed and unmoving. The midway is attached to a large platform at the centre of which resides the all important, never changing Aroundland. Aroundland is not on the platform but on firm, fixed earth. The platform on which is located the midway rotates regularly in a counterclockwise direction. This is why when we look at the midway everything is observed to be flying by in a counterclockwise direction."
>
> The young student did not think this was a correct interpretation. He spent most of his life trying to devise an experiment to show that it was really Aroundland that was rotating. But due to frequent spells of dizziness he was not successful.



Page from *Physics: an Aroundland Endeavour*

Suggest an experiment to prove that Aroundland goes around.

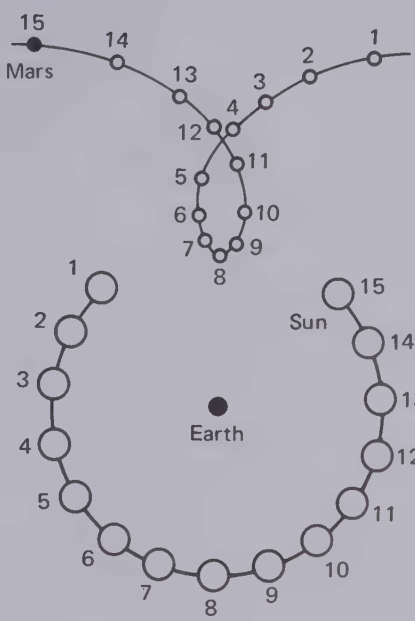
*7.5 Why was Copernicus called "the quiet revolutionary"?

*7.6 Using the values for radii of planetary orbits on page 26 suggest the radii for the next planet out from the sun. What is the basis for your value? (You might like to read about the Titus-Bode Relation in an astronomy text.)

Section B

*7.7 Explain, using the pages describing the change of reference from the earth to the sun, how Copernicus was able to determine the relative distances of planets from the sun.

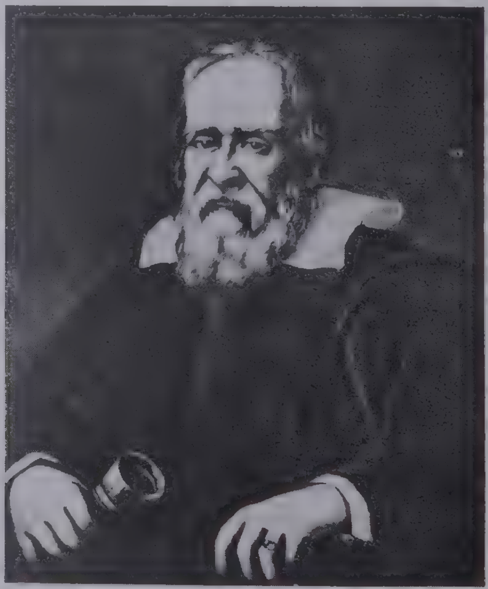
*7.8 The diagram shows numbered positions of the sun and Mars (on its epicycle) at equal time-intervals in their motion around the earth, as described in the Ptolemiac system. You can easily redraw the relative positions to change from the earth's frame of reference to the sun's. Mark a sun-sized circle in the middle of a thin piece of paper; this will be a frame of reference centered on the sun. Place the circle over each successive position of the sun, and trace the corresponding numbered position of Mars and the position of the earth. (Be sure to keep the piece of paper straight.) When you have done this for all 15 positions, you will have a diagram of the motions of Mars and the earth as seen in the sun's frame of reference.



7.9 The largest observed annual shift in star position is actually 1/2500 of a degree. What is the distance (in AU's) to this closest star?

Chapter 8 *A New Universe Appears*
The Work of Kepler and Galileo

Kepler
(1571-1630)



Galileo
(1564-1642)

A New Universe Appears
The Work of Kepler and Galileo

Chapter Eight

Johannes Kepler, Keppler, Khepler, Kheppler or Keplerus was conceived on 16 May, A.D. 1571, at 4.37 a.m., and was born on 27 December at 2.30 p.m., after a pregnancy lasting 224 days, 9 hours, and 53 minutes. The five different ways of spelling his name are all his own, and so are the figures relating to conception, pregnancy, and birth, recorded in a horoscope which he cast for himself. The contrast between his carelessness about his name and his extreme precision about dates reflects, from the very outset, a mind to whom all ultimate reality, the essence of religion, of truth and beauty, was contained in the language of numbers.

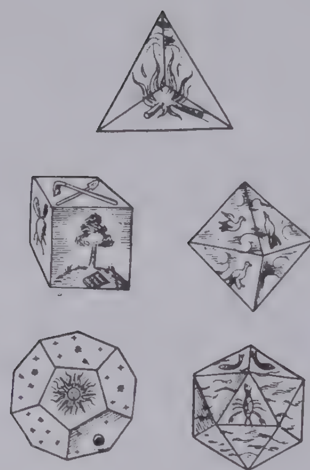
Arthur Köestler *The Sleepwalkers*

Arthur Koestler is the author of an excellent book on the history of astronomy, called The Sleepwalkers London: G. B. Hutchinson, © 1959 Arthur Koestler.

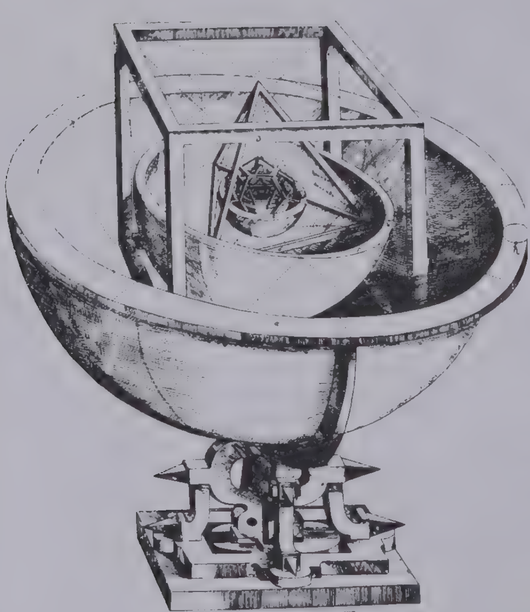
Johannes Kepler is remembered as the formulator of three laws of planetary motion. These laws modified the Copernican model, permitted accurate prediction of planetary positions, and set the stage for the brilliant synthesis of Isaac Newton. The formulation of these laws required many years of observation and much frustration. Kepler was motivated by a desire to show perfection in the heavens. In this chapter we shall follow the progressive development of these laws by discussing Kepler's early theories, his associations with other scholars, and the final analysis that led to his major hypotheses concerning planetary motions.

8.1 Mysterium Cosmographicum

The quest of a scientist depends in part upon the scientific framework of his era and the questions he asks. Kepler regarded the search for a planetary model as a cosmic mystery, the solution of which would reveal a design of God. He accepted the Copernican theory and was fascinated by the question, "Why are there only six planets?" Kepler's answer was based on his belief that this number was by divine plan rather than chance. This



The five "perfect solids" taken from Kepler's *Harmonices Mundi* (Harmony of the World). The cube is a regular solid with six square faces. The dodecahedron has twelve five-sided faces. The other three regular solids have faces which are equilateral triangles: the tetrahedron has four triangular faces, the octahedron has eight triangular faces, and the icosahedron has twenty triangular faces.



answer led to a model of the solar system that had as a basis the five solid figures, or regular polyhedra, used by Plato in his description of the fundamental parts of matter. It had been proved by Euclid that there are only five regular convex solids. He believed that his model provided a geometric perfection which reflected that perfection of deity.

Kepler's geometric model of the universe had the sun at the centre and contained each of the perfect solids as a separator between planetary shells. This multi-layered model was built as follows. In the centre was the sun surrounded by the sphere of Mercury. Between Mercury and Venus was placed the octahedron. The icosahedron separated the Earth and Venus. The sphere of the Earth was surrounded by the dodecahedron which in turn was encased in the sphere of Mars. A tetrahedron was placed between Mars and Jupiter. Jupiter was surrounded by a cube. The cube was surrounded by the sphere of the outermost planet Saturn. Perhaps the amazing thing is that this model was a reasonably accurate description of the planetary distances determined by Copernicus. Thus Kepler provided an explanation for the number of planets and their distances from the sun. In doing this he believed that he had solved a major riddle of the universe.

His description was published in a book *Mysterium Cosmographicum* in 1596 and was regarded by Kepler as one of his major contributions to astronomy. It is now regarded as a very interesting construction which, however coincidently approximate, has no usefulness in describing the positions of the nine planets now known to orbit the sun.

The attempt to find this model and the publishing of *Mysterium Cosmographicum* had three important consequences.

1. In publishing *Mysterium Cosmographicum*, Kepler became the first scholar to openly accept the Copernican system.
2. Kepler realized in his work that he required more observational data to verify the model and believed that many of the Copernican figures were incorrect.
3. Through the *Mysterium Cosmographicum*, Kepler received the publicity that was to open communication with Tycho Brahe and Galileo. Soon after this publication (in 1600), Kepler accepted an offer to work with Tycho Brahe at his observatory near Prague.

Tycho Brahe, the man to whom Kepler turned for observations that would confirm his model of the perfect cosmos, was the foremost observational astronomer of his time. He had excellent instruments built, and made many modifications to them to increase their accuracy. Because of the accuracy of his observations, Tycho was unable to accept the Copernican system.

He believed that if the earth travelled about the sun, measurements of a star's position would show parallax. He spent much time observing and searching charts of star positions for this effect. He could not detect parallax, even though his star positions were measured to an accuracy of 1/60 of a degree, nor did he realize that the stars were positioned at such a great distance as to be immeasurable with his instruments. After

reading the *Mysterium Cosomographicum* he recognized he could use Kepler in his analyses and invited the young astronomer to become his assistant. When Tycho Brahe died less than two years after their first meeting, Kepler inherited his observational data and the title "Imperial Mathematician".

You might like to read an article entitled "The Celestial Palace of Tycho Brahe" in *Scientific American* Feb. 1961.

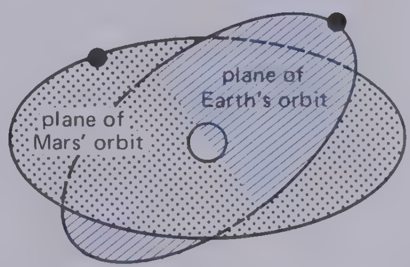
*Q1 How would Kepler's *Mysterium Cosmographicum* be received by scientists today?
Q2 What did Kepler hope to gain from his association with Tycho Brahe?
Q3 What did Tycho Brahe hope to gain from his association with Kepler?
See problem 8.1 on page 49.

8.2 The Investigation of Mars

Shortly after his arrival in Prague, Kepler was given the task of analysing the orbit of Mars. He boasted that the analysis would take him about eight days, but he was to find that it took nearly eight years. Kepler's struggle with the analysis of the orbit of Mars is portrayed in his book, *Astronomia Nova*, (the *New Astronomy*), which records his persistence, carelessness, brilliance, and final success. In writing his account, Kepler thought of himself as an explorer and recorded for posterity, in a manner similar to a seventeenth century explorer, not only his successes, but each path that led to failure and each mistake. As a result, the book, although it portrayed the working of a great mind, was very difficult to read and many major achievements lay hidden in the text.

Fortunately Kepler had made a major discovery earlier which was crucial to his later work. He found that the orbits of the earth and other planets were in planes which passed through the sun. Ptolemy and Copernicus required special explanations for the motion of planets north and south of the ecliptic, but Kepler found that these motions were simply the result of the orbits lying in planes tilted to the plane of the earth's orbit.

Although he used Ptolemy's geometric devices, Kepler in his initial study of the orbit of Mars made three important innovations. He believed that the sun must be at the centre of the system, that the plane of the planetary orbits was fixed in space, and that the speed of the planet in its circular orbit was not constant but depended on its distance from the sun. Kepler considered the sun as the source of the driving force of the system. He was still thinking in terms of circles, and so positioned an equant and eccentric to explain some of Tycho's observations. After much tedious calculation, he satisfied several of Tycho's measurements of right ascension. His initial excitement turned to despair when he discovered many errors in the predicted declinations. After adjusting the eccentric, he managed to satisfy the positions to within 8 minutes. He then felt forced to reject this solution because the deviation was greater than the inaccuracy that Tycho had calculated for star positions. (Very few of Tycho's measurements had been in error by more than 2 minutes.) In his *Astronomia Nova*, Kepler wrote,



The diagram depicts a nearly edge-on view of orbital planes of earth and another planet, both intersecting at the sun.

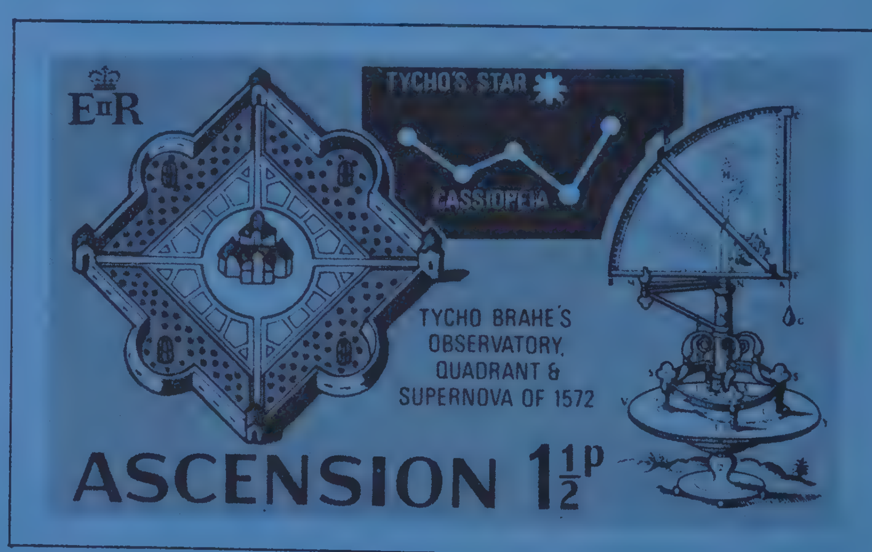
1 minute equals 1/60 of a degree.

> Since divine kindness granted us Tycho Brahe, the most diligent observer, by whose observations an error of eight minutes in the case of Mars is brought to light in this Ptolemaic calculation, it is fitting that we recognize and honour this favour of God with gratitude of mind. Let us certainly work it out, so that we finally show the true form of the celestial motions (by supporting ourselves with

You may plot a Mars orbit by doing Experiment 8.2, *Mars' Orbit*, pg. 123.

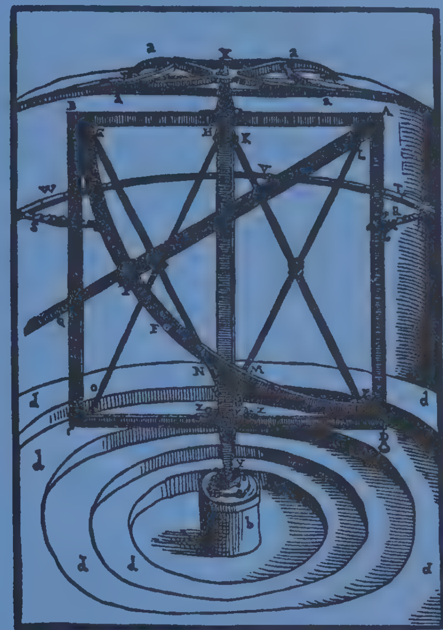
Main spheres in Tycho Brahe's system of the universe. The earth was fixed and was at the centre of the universe. The planets revolved around the sun, while the sun, in turn, revolved around the fixed earth.

Tycho Brahe
(1546-1601)



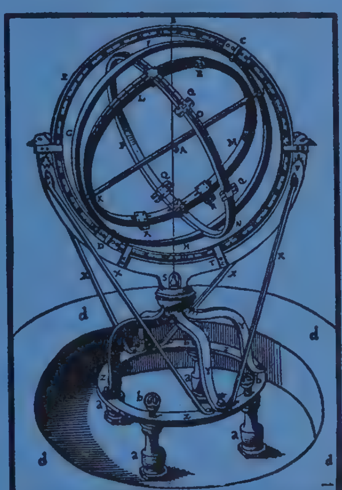
SEXTANS ASTRONOMICUS TRIGO-
NICUS PRO DISTANTIIS RIMANDIS

QUADRANS MAGNUS CHALIBEUS,
IN QUADRATO ETIAM CHALIBEO COMPREHENSUS,
UNAQUE AZIMUTHALIS

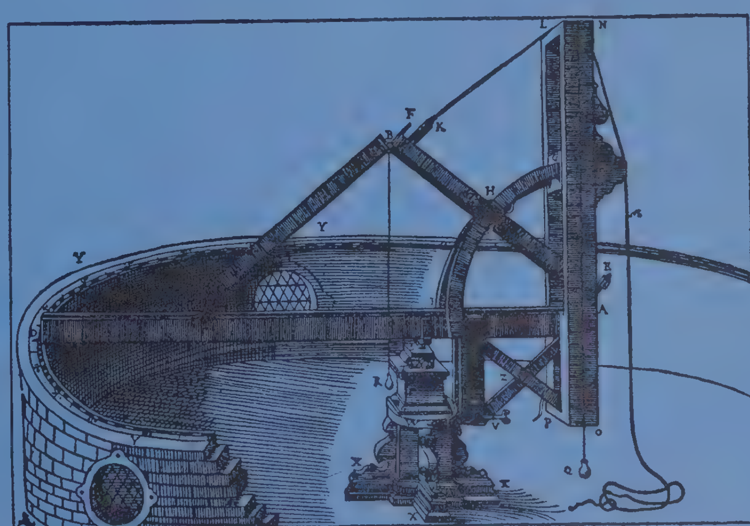


The instruments of Tycho Brahe. Most of Brahe's instruments were destroyed in 1619 during the Thirty Years War.

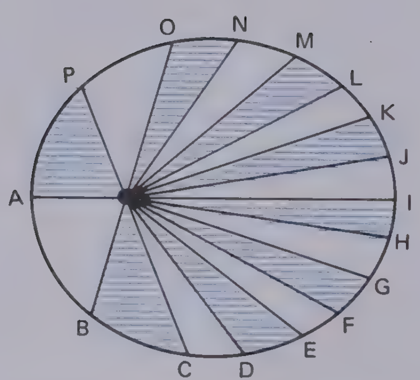
ARMILLÆ ZODIACALES



PARALLATICUM ALIUD SIVE REGULÆ
TAM ALTITUDINES QUAM AZIMUTHA
EXPEDIENTES



these proofs of the fallacy of the suppositions assumed). I myself shall prepare this way for others in the following chapters according to my small abilities. For if I thought that the eight minutes of longitude were to be ignored, I would already have corrected the hypothesis which he had made earlier in the book and which worked moderately well. But as it is, because they could not be ignored, these eight minutes alone have prepared the way for reshaping the whole of astronomy, and they are the material which is made into a great part of this work.

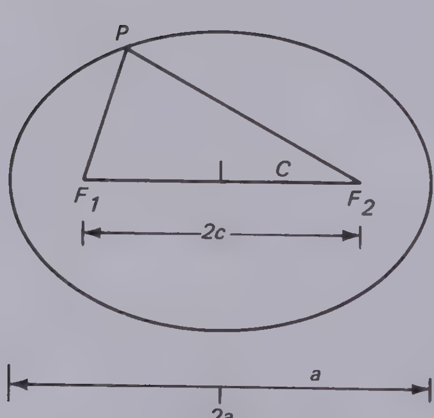


Kepler's *Law of Areas.* A planet moves along its orbit at a rate such that the line from the sun to the planet sweeps over areas which are proportional to the time-intervals. The time taken to cover *AB* is the same as that for *BC, CD,* and so on.
Since the planet travels from *H* to *J* in the same time it travels from *P* to *B*, one can see that the speed at perihelion is greater than at aphelion.

Thus he was forced to reject a circular orbit for Mars along with nearly two years of work. The question posed by Plato now had to be changed. Kepler no longer sought the circles or combinations of circles along which a planet moved at constant speed. He questioned, **"What was the shape of the orbit of Mars?"** and **"How did the speed change in that orbit?"** Often the key to the successful resolution of a problem lies in asking the best question, not in obtaining the correct answer to an inadequate question.

Before determining the shape of the orbit of Mars, Kepler used Tycho Brahe's observations of Mars to determine the shape of the earth's orbit and the rate at which it travelled about the sun. In doing this calculation, he observed that the earth moved fastest when closest to the sun. This confirmed his belief that the sun somehow directed the planets in their motion. He wrote that he believed this direction to come from a type of magnetism. From this analysis he formulated the law which accounts for the variations of a planet's speed in the orbit. It is called the *Law of Equal Areas* and states that *the line joining the sun to a planet sweeps out equal areas in equal times as the planet travels in its orbit.* This means that speed changes from a maximum at perihelion to a minimum at aphelion. The importance of the sun's central role in this concept strengthened Kepler's belief in the Copernican system.

Following this success, Kepler was to spend a full year trying to fit the observations of Mars to an oval (egg-shaped) path. The true shape, the ellipse, continuously eluded him. He wrote in a letter to a friend, "If only the shape were a perfect ellipse, all the answers could be found in Archimede's and Appolonius' work". These Greek mathematicians had discussed the properties of the ellipse in their texts. It was nearly two years and many attempts later that Kepler finally realized that the locus he sought was, in fact, the ellipse, the very figure he had come so close to considering many months before! From this analysis came the *Law of Elliptical Orbits.*



An ellipse showing the semi-major axis a, and the two foci F_1 and F_2. The shape of an ellipse is described by its eccentricity e, where $e = c/a$.

Thus the six years of labour resulted in two simple statements.

1. The orbit of the planets about the sun is an ellipse having the sun at one focus.
2. The line from the sun to the planet sweeps out equal areas in equal times.

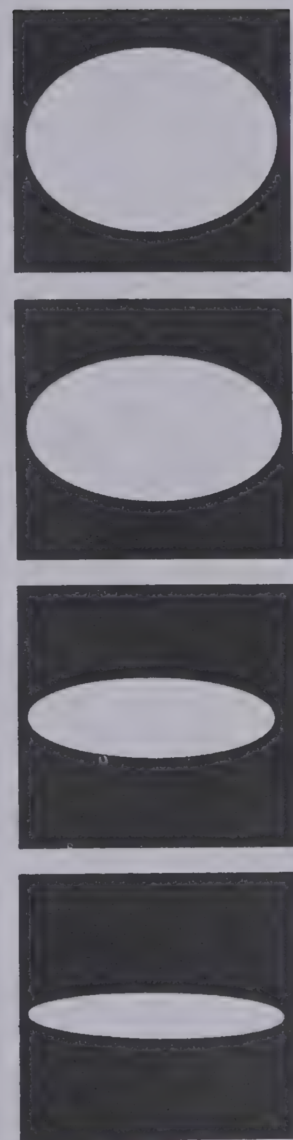
These laws are beautiful in their simplicity. The first gives us the shape of the orbit and the second describes the rate of the planet's motion. Together they enable an astronomer to predict a planet's position.

The work of Kepler illustrates the enormous change in outlook in Europe that had begun well over two centuries earlier. Kepler still shared the ancient idea that each planet had a "soul", but he refused to rest his explanation of planetary motion on this idea. Instead, he began to search for physical causes. Whereas Copernicus and Tycho were willing to settle for geometrical models by which planetary positions could be predicted, Kepler was one of the first to seek dynamic causes for the motions. This new desire for physical explanations marks the beginning of one of the chief characteristics of modern physical science.

Like Kepler, we believe that our observations represent some aspects of a reality that is more stable than the changing emotions and wishes of human beings. Like Plato and all subsequent scientists, we assume that nature is basically orderly and consistent, and, therefore, understandable in a simple way. This faith has led to great theoretical and technical gains. Kepler's work illustrates one of the scientific attitudes—to regard a wide variety of phenomena as better understood when they can be summarized by simple law, preferably one expressed in mathematical form.

After Kepler's initial joy over the discovery of the Law of Elliptical Paths, he may have asked himself the question: Why are the planetary orbits elliptical rather than some other geometrical shape? While we might understand Plato's desire for uniform circular motions, nature's insistence on the ellipse is a surprise.

In fact, there was no satisfactory answer to this question until Newton showed, almost eighty years later, that these elliptical orbits were necessary results of a more general law of nature. Let us accept Kepler's laws as rules that contain the observed facts about the motions of the planets. As *empirical laws*, they each summarize the data obtained by observation of the motion of any planet. The Law of Orbits, which describes the paths of planets as elliptical around the sun, gives us all the possible positions each planet can have if we know the size and eccentricity of the orbit. That law, however, does not tell us when the planet will be at any one particular position on its ellipse or how rapidly it will be moving then. The Law of Areas does not specify the shape of the orbit, but does describe how the angular speed changes as the distance from the sun changes. Clearly these two laws complement each other. With these two general laws, and given the values for the size and eccentricity of the orbit (and a starting point), we can determine both the position and angular speed of a given planet at any time, past or future. Since we can also find where the earth is at the same instant, we can calculate the position of the planet as it would have been or will be, as seen from the earth.



$e = 0.3$

$e = 0.5$

$e = 0.8$

$e = 0.98$

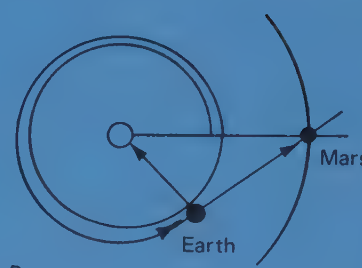
Ellipses of different eccentricities. (The pictures were made by photographing a saucer at different angles.)

See Experiment 8.1, *The Ellipse*, pg. 121.

To derive the earth's orbit he began by considering the moments when the sun, earth, and Mars were essentially in a straight line (Fig. A). After 687 days, as Copernicus had found, Mars would return to the same place in its orbit (Fig. B). Of course, the earth at that time would *not* be at the same place in its own orbit as when it was the first observation was made. But, as Fig. B and Fig. C indicate, the directions to the sun and Mars as they might be seen from the earth against the fixed stars would be known. The crossing point of the sight-lines to the sun and to Mars must be a point on the earth's orbit. By working with several groups of observations made 687 days apart (one Mars "year"), Kepler was able to determine fairly accurately the shape of the earth's orbit.

The orbit Kepler found for the earth appeared to be almost a circle, with the sun a bit off-centre. From his plotted shape and the record of the apparent position of the sun for each date of the year, he could locate the position of the earth and its orbit, and its speed along the orbit. You made a similar plot in the experiment, The Shape of the Earth's Orbit.

A



B

C

With the orbit and timetable of the earth known, Kepler could reverse the analysis and find the shape of Mars' orbit. For this purpose he again used observations separated by one Martian year. Because this interval is somewhat less than two earth years, the earth is at different positions in its orbit at the two times, so the two directions from the earth toward Mars differ. Where they cross is a point on the orbit of Mars. From such pairs of observations Kepler fixed many points on the orbit of Mars. The diagrams illustrate how two such points might be plotted.

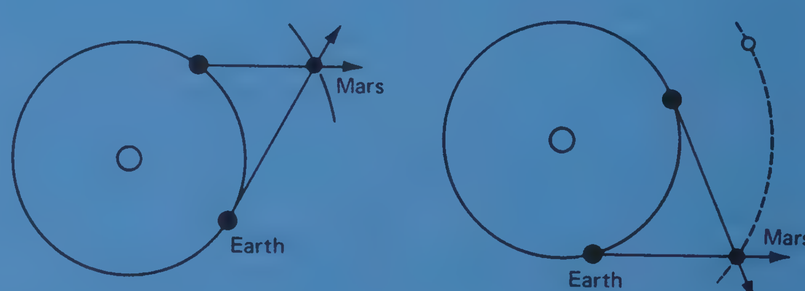


Table 8.1 *The Eccentricities of Planetary Orbits*

PLANET	ORBITAL ECCENTRICITY	NOTES
Mercury	0.206	Too few observations for Kepler to study.
Venus	0.007	Nearly circular orbit.
Earth	0.017	Small eccentricity.
Mars	0.093	Largest eccentricity among planets Kepler could study.
Jupiter	0.048	Slow moving in the sky.
Saturn	0.056	Slow moving in the sky.
Uranus	0.047	Not discovered until 1781.
Neptune	0.009	Not discovered until 1846.
Pluto	0.249	Not discovered until 1930.

Q4 State Kepler's Law of Elliptical Orbits and his Law of Equal Areas.
Q5 Did these laws explain how a planet moved or why a planet moved?
Q6 Why did Kepler conclude that Plato's problem, to describe the motions of the planets by combinations of circular motions, could not be solved?
Q7 Where in its orbit does a planet move the fastest?

See also problems 8.2 to 8.4 on page 49.

8.3 Kepler's Law of Periods

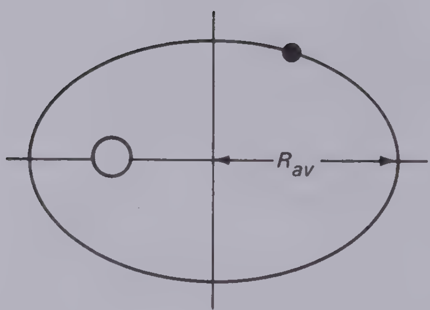
Kepler's first two laws were published in 1609 in his book *Astronomia Nova*, but he was still dissatisfied because he had not yet found any relation among the motions of the different planets. Each planet seemed to have its own elliptical orbit and speeds, but there appeared to be no overall pattern relating all planets to one another. Kepler had begun his career by trying to explain the number of planets and their spacing. He was convinced that the observed orbits and speeds could not be accidental, but that there must be some regularity linking all the motions in the solar system. His conviction was so strong, that he spent years examining many possible combinations of factors to find, by trial and error, a third law that would relate all the planetary orbits. His long search, almost an obsession, illustrates a belief that has run through the whole history of science: Despite apparent difficulties in getting a quick solution, underneath it all, nature's laws are understandable. This belief is to this day a chief source of inspiration in science, often sustaining the spirit in periods of seemingly fruitless labour. For Kepler it made endurable a life of poverty, illness, and other personal misfortunes, so that in 1619 he could write triumphantly in his *Harmony of the World:*

. . . after I had by unceasing toil through a long period of time, using the observations of Brahe, discovered the true relation . . . overcame by storm the shadows of my mind, with such fullness of agreement between my seventeen year's labour on the observations of Brahe and this present study of mine that I at first believed that I was dreaming. . . .

Kepler's Law of Periods, also called the "Harmonic Law", related the periods of the planets to their average distances from the sun. The period is the time taken to go once completely around the orbit. The law states that the *squares of the periods of the planets are proportional to the cubes of their average distances from the sun.* In the short form of algebra, calling the period T and the average distance R_{av}, this law can be expressed as:

$$T^2 \propto R_{av}^3 \text{ or } T^2 = kR_{av}^3 \text{ or } \frac{T^2}{R_{av}^3} = k,$$

where k is a constant. When T is measured in years and R in A.U. the value of k is unity, as shown in Table 8.2. Because this relation applies to all the planets and even to comets in orbit around the sun, we can use it to find the period of any planet once we know its average distance from the sun, and *vice versa.*



The value of R_{av} for an ellipse is just half the major axis.

Kepler's three laws are so simple that their great power may be overlooked. When they are combined with his discovery that each planet moves in a plane passing through the sun, they let us derive the past and future history of each planet from only six quantities. Two of these quantities are the size and eccentricity of the orbit, three others are angles that relate the plane of the orbit to that of the earth's orbit, while the sixth tells where in its orbit the planet was on any one certain date.

Table 8.2

	COPERNICUS' VALUES			MODERN VALUES		
PLANET	PERIOD T, (YEARS)	AVERAGE DISTANCE R_{av} (AU)	$\frac{T^2}{R_{av}^3}$	PERIOD T, (YEARS)	AVERAGE DISTANCE R_{av} (AU)	$\frac{T^2}{R_{av}^3}$
Mercury	0.241	0.38	1.06	0.241	0.387	1.00
Venus	0.614	0.72	1.01	0.615	0.723	1.00
Mars	1.881	1.52	1.01	1.881	1.523	1.00
Jupiter	11.8	5.2	0.99	11.862	5.20	1.00
Saturn	29.5	9.2	1.12	24.458	9.54	1.00

It is astonishing that in this manner the past and future positions of each planet (and, as we now know, also every comet) can be derived in a simpler and more precise way than through the multitude of geometrical devices on which all other planetary theories depended, whether those of Ptolemy, Copernicus, or Tycho. With different assumptions and procedures Kepler had at last solved the astronomical problem on which so many great men had worked over the centuries. Although he had to abandon the geometrical devices of the Copernican system, Kepler did

depend on the Copernican viewpoint of a sun-centered universe. None of the earth-centered models could have led to Kepler's three laws.

In 1627, after many troubles with his publishers and Tycho's heirs, Kepler finally published a set of astronomical tables. In these tables, Kepler combined Tycho's observations and the three laws in a way that permitted accurate calculations of planetary positions for any time, whether in the past or future. These tables remained useful for a century, until telescopic observations of greater precision replaced those of Tycho.

Kepler's scientific interest was not confined to the planetary problem alone. Like Tycho, who was much impressed by the new star of 1572, Kepler observed and wrote about new stars that appeared in 1600 and 1604. His observations and interpretations added to the impact of Tycho's earlier observations that changes did occur in the starry sky. As soon as Kepler learned of the development of the telescope, he spent most of a year making careful studies of how the images were formed. These he published in a book titled *Dioptrice* (1611), which became the standard work on optics for many years. Later, in 1627 Kepler published a slim volume entitled the *Tabulae Rudolphinae* which used his model of the solar system to predict planetary positions. This volume was for many years the primary source for predictions of planetary position. It combined the observational skills of Brahe with the mathematical model of Kepler.

In addition to a number of important books on mathematical and astronomical problems, Kepler wrote a popular and widely read description of the Copernican system as modified by his own discoveries. This added to the growing interest in and acceptance of the sun-centered model of the planetary system.

*Q8 State Kepler's Law of Periods.

*Q9 Using this law and the chart on page 85, determine the period of the planet Neptune whose average distance from the sun is 30 AU.

See problems 8.5 to 8.8 on page 49.

8.4 The New Concept of Physical Law

One general feature of Kepler's lifelong work has had a far reaching effect on the way in which all the physical sciences developed. When Kepler began his studies, he still accepted Plato's assumptions about the importance of geometric models and Aristotle's emphasis on natural place to explain motion. But later he came to concentrate on algebraic laws describing how planets moved. His successful statement of empirical laws in mathematical form helped to establish the use of the *equation* as the normal form for stating laws in physical science.

More than anyone before him, Kepler expected an acceptable theory to agree with precise and quantitative observation.

From Tycho's observations he learned to respect the power of precision measurement. Models and theories can be modified by human ingenuity, but good data endure regardless of changes in assumptions or viewpoints.

Kepler went beyond observation and mathematical description and attempted to explain motion in the heavens by the action of physical forces. In Kepler's system the planets no longer were thought to revolve in their orbits because they had some divine nature or influence, or because this motion was "natural", or because their spherical shapes provided a self-evident explanation for circular motion. Rather, Kepler was the first to look for a physical law based on observed phenomena which would be able to describe the whole universe in a detailed quantitative manner. In an early letter he expressed his guiding thought:

> I am much occupied with the investigation of the physical causes. My aim is to show that the celestial machine is to be likened not to a divine organism but rather to a clockwork . . . insofar as nearly all the manifold movements are carried out by means of a single, quite simple magnetic force, as in the case of a clockwork, all motions are caused by a simple weight. Moreover, I show how this physical conception is to be presented through calculation and geometry. (Letter to Herwart, 1605.)

William Gilbert (1544-1603) author of *De Magnete.*

To show the celestial machine to be like a clockwork propelled by a single force was a prophetic goal indeed! Stimulated by William Gilbert's work on magnetism published a few years earlier, Kepler could imagine magnetic forces from the sun driving the planets along their orbits. This was a reasonable and promising hypothesis. As it developed, the basic idea that a single kind of force controls the motions of all the planets was correct; but the force is not magnetism, and it is needed not to keep the planets moving forward, but to deflect their paths so as to form closed orbits.

Kepler's statement of empirical laws reminds us of Galileo's suggestion made at about the same time, that we deal first with the how of motion in free fall and then with the why. A half century later Newton used the concept of gravitational force to tie together Kepler's three planetary laws with laws of terrestrial mechanics thereby providing a magnificent synthesis. (See Chapter 9.)

8.5 Galileo Galilei: The View Through a Telescope

Perhaps Galileo was not the first to examine the heavens through a telescope but he was certainly the first to publish the results of this examination.

Galileo, a contemporary of Johannes Kepler, made significant contributions to the study of astronomy. Unlike Copernicus, however, Galileo was anxious to make his observations and opinions widely known, and as a result, he became the focus of a confrontation between scientific and religious beliefs. In the following sections we shall examine Galileo's contribution to an understanding of the universe and the nature of the resulting controversy.

In 1609, having heard a description of the principles of a telescope, Galileo manufactured a small telescope which he

presented to the Senate of Venice. They responded by giving him a generous annual allowance. Galileo then manufactured a telescope, for astronomical use, which magnified objects about thirty times. Galileo wrote a booklet entitled *Sidereus Nuncius*, (The *Starry Messenger*), to tell of his discoveries with this new device.

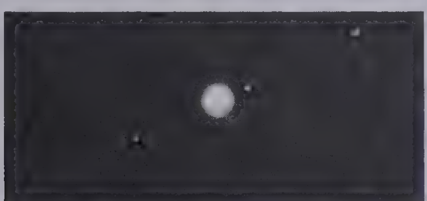
See Activity 8.5, pg. 133.

One of the first objects he observed through his telescope was the moon. If you have not examined the moon with a telescope, borrow either a small telescope or a pair of binoculars and try it. You will observe the same view that Galileo recorded almost 400 years ago in *The Starry Messenger*.

> . . . the surface of the moon is not smooth, uniform, and precisely spherical as a great number of philosophers believe it (and other heavenly bodies) to be, but is uneven, rough, and full of cavities and prominences, being not unlike the face of the earth, relieved by chains of mountains, and deep valleys.

Turning his telescope from the moon, Galileo saw that the hazy patches of the Milky Way were formed by thousands of individual stars. Also, the dark regions of the sky were seen to contain many stars not visible to the unaided eye. He saw planets as disc-shaped objects, but the distant stars, even when observed through the telescope, appeared not larger but brighter. The observation that the stars even when magnified by the telescope appeared as point-images showed that they must be at much greater distances than earlier theories had indicated. The most exciting sight recorded by Galileo was the four moons that were observed orbiting the planet Jupiter. He named these four celestial bodies the "Medician Stars" in honour of the reigning house of Tuscany.

Galileo calculated the height of some lunar mountains by measuring the length of their shadows.



Galileo used the astronomical telescope as a scientific instrument to show fallacies in the Aristotelian view of the universe. The believers in Aristotle's scheme of the universe viewed Galileo's recording of an uneven moon surface as a challenge to the perfection of the heavens. The observation of stars not visible to the naked eye made less probable the idea that stars were placed in the heavens to please man and help him understand his place on earth, since many could be seen only with a telescope. The universe was seen to be immense and the stars so distant that perhaps, as suggested by Copernicus, their parallax was too small to measure. This would remove a major objection to the models proposed by Copernicus and much earlier by Aristarchus. The four moons revolving around the planet Jupiter showed that the earth was *not* the centre of all celestial revolutions. Galileo considered this observation to be of major importance and he wrote in his text:

> Moreover, we have an excellent and exceedingly clear argument to put at rest the scruples of those who can tolerate the revolution of the planets about the sun in the Copernican system, but are so disturbed by the revolution of the single moon around the earth while both of them describe an annual orbit around the sun, that they consider this theory of the universe to be impossible.

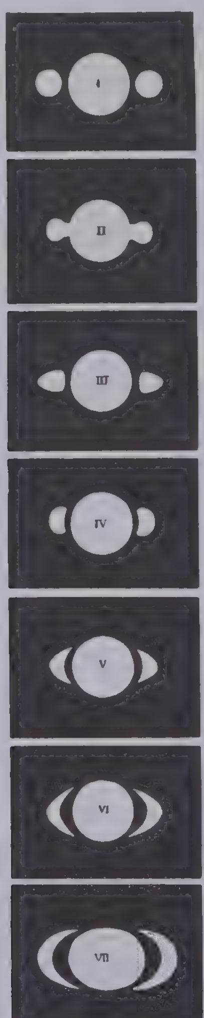
A translation of *The Starry Messenger* has been made by Stillman Drake. It is available in *Discoveries and Opinions of Galileo,* a Doubleday publication.

Unlike the writings of Copernicus and Kepler, *The Starry Messenger* became a best seller that was widely read and discussed. Probably this was because of the brevity and readability of Galileo's text. You can read *The Starry Messenger* in about an hour and will find it interesting even today.

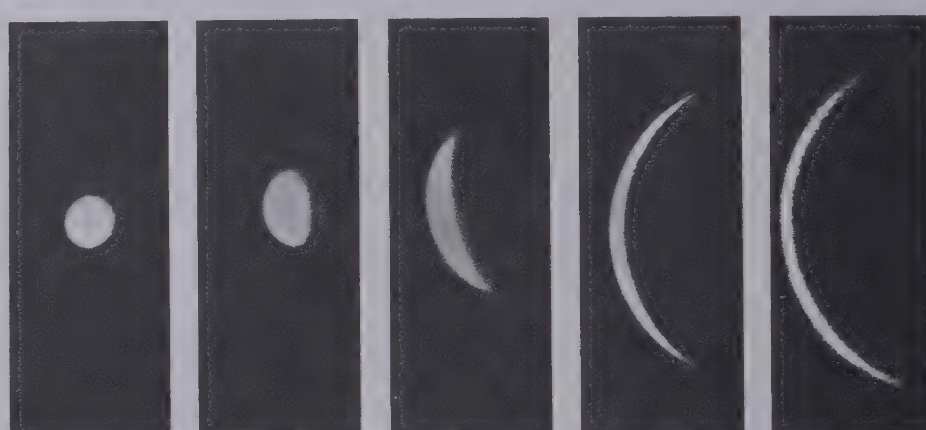
Many people welcomed this new view of the night sky but others refused to believe their eyes or thought the observations to be a trick of the instrument. People were not happy to have their beliefs challenged by a few observations through a suspicious device. One of the few to immediately accept the observations of Galileo was Johannes Kepler. He viewed Galileo's theories as supporting evidence for his own belief in the Copernican system and wrote Galileo praising his efforts.

Galileo offered a prize to anyone who could construct an optical tube that would show four moons about one planet and not about all the other stars.

Galileo continued to use his telescope with remarkable results. By projecting an image of the sun on a screen, he observed sunspots. This was additional evidence that the sun, like the moon, was not perfect in the Aristotelian sense: it was disfigured rather than even and smooth. From his observation that the sunspots moved across the face of the sun in a regular pattern, he concluded that the sun rotated with a period of about 27 days.



Drawings of Saturn made in the seventeenth century.



Photographs of Venus at various phases with a constant magnification.

He also found that Venus showed all phases, just as the moon does (see diagrams). Therefore, Venus must move completely around the sun as Copernicus and Tycho had believed, rather than be always between the earth and sun as the Ptolemaic astronomers assumed. Saturn seemed to carry bulges around its equator, as indicated in the drawings, but Galileo's telescopes were not large enough to show that they were rings. With his telescopes he collected an impressive array of new information about the heavens. All of it seemed to contradict the basic assumptions of the Ptolemaic world scheme.

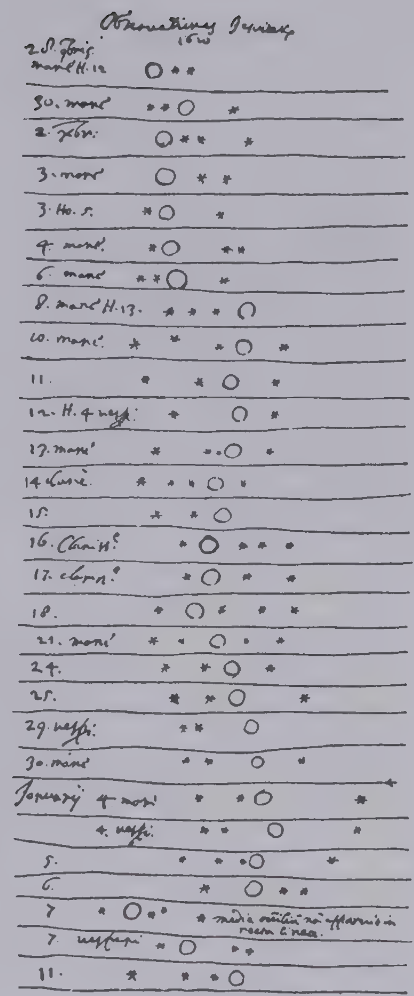
*Q10 List the observations stated in *The Starry Messenger* and explain how each appeared inconsistent with Aristotle's view of the universe.

*Q11 Using the photographs of the phases of Venus,

estimate the ratios of the closest approach and farthest position of Venus as seen from the earth.

*Q12 Show by means of a diagram why the planet Venus exhibits phases.

See problems 8.9 and 8.10 on page 49.



These sketches of Galileo are from the first edition of *The Starry Messenger.*

8.6 Science and Freedom

Following his telescopic observations, Galileo became strongly convinced of the truth of the Copernican model of the solar system. The wide circulation of Galileo's book brought much attention to the earlier writings of Copernicus. An examination of *De Revolutionibus* by the Church resulted in its being placed on the *Index of Forbidden Books* in 1616. It was removed four years later after it had been modified to state that the Copernican model was merely a mathematical model and was not to be considered the "true" picture of the solar system. In the same year that the Copernican thesis was banned by the Church as being contrary to scriptures, Galileo was forbidden to promote or defend it. Galileo was a religious man who believed that the Church, in taking this action, was making a regretable mistake. He wrote:

> I would entreat those wise and prudent Fathers that they should with all diligence consider the difference that exists between demonstrative knowledge and knowledge where opinion is possible: to the end, that weighing well in their minds, with what force necessary conclusions compel acceptance, they may the better ascertain for themselves that it is not in the power of those who profess the demonstrative sciences to change their opinions at pleasure and to apply themselves now on one side and now on the other; that there is a great difference between commanding a mathematician or a philosopher and disposing of a merchant or lawyer; and that the demonstrated conclusions touching the things of nature and of the heavens cannot be changed with the same facility as opinions about what is legal or not in a contract, rent, or bill of exchange.

Or, as he put it, "The purpose of scripture is to teach us how to go to heaven, not how the heavens go". Galileo obeyed the decree and did not publicly defend the Copernican thesis for some time. However, he continued to write letters and privately tried to explain his position.

In 1623, Cardinal Barberini, a friend of Galileo, was elected Pope Urban VIII. Soon after this Galileo started work on his *Dialogue Concerning the Two Chief World Systems* which very persuasively explained his position regarding the Copernican system. Galileo modified this book at the suggestion of the Church to include a preface and an ending which defended the Ptolemaic model and suggested that the Copernican model was just a useful mathematical idea, although the bulk of the text strongly advocated the Copernican hypothesis. With these modifications, he believed he was publishing with the permission of the Church. The *Dialogue* was published in 1632. Galileo probably underestimated the impact of his book and the consequences of its publication. It was widely read as a defence of the Copernican system.

One reason for the popularity of this text was that, unlike other scientific works, it was written in Italian rather than Latin.

Galileo was summoned to Rome by the Inquisition, where he was confined, questioned and perhaps threatened with torture. Testimony presented against him used not only quotations from his book but from the many verbal defences he had made of the Copernican system. He was forced by the Inquisition to recant his earlier beliefs as being the result of false pride and to state that he would never again teach or believe in the Copernican system. In some biographies, it suggests that he murmured "E pur si muove"—"and yet it does move" at the time of his recantation. About this Bertrand Russell wrote "It was the world that said this—not Galileo".

The trial of Galileo has been used by writers to focus our attention on the need for freedom in scientific endeavours. But what is meant by freedom in science? The following list was suggested by a group of students who had studied the confrontation of Galileo and the Church.

A scientist should have:

1. The freedom to pursue scientific investigations.
2 The freedom to publicize and teach the theory which he believes to be true.
3. The freedom to publish and discuss the results of his investigations.

Many students suggested that these freedoms are basic freedoms of mankind and should not be limited to scientists alone.

Conflicts involving freedom and science are not restricted to instances in the distant past. Recent history presents us with many examples of such conflicts. In 1925, in Tennessee, the "Monkey Trial" was held, attacking the teaching in the schools of Darwin's theory of biological evolution because it conflicted with certain types of biblical interpretation. In Nazi Germany the discussion and teaching of the Theory of Relativity was banned because Einstein's Jewish parentage was said to invalidate his work. In the United States, in 1954, American physicist Robert Oppenheimer was denied access to scientific papers on the grounds that his political beliefs made him a security risk. In Russia in 1948, Trofim Lysenko, Director of Genetics, forced Soviet geneticists to disregard established theories because they conflicted with political doctrines.

Many scientific investigations in the twentieth century are very expensive undertakings. They require the financial resources of either governments or large corporations. In return for this assistance, the governments or corporations often put certain restrictions on the scientists. These restrictions often involve conditions of secrecy forbidding the publication of the results of scientific investigations. Or, they limit the area of investigation to a certain field where it may eventually achieve a fixed goal. Landing a man on the moon, finding a cure for cancer, or developing a new type of plastic, are examples of such goal-oriented research. Are we to regard such restrictions as conflicting with a scientist's freedom?

In 1968, the Canadian Senate appointed a special committee on science policy for Canada to define a direction for

Suggested for further reading:

de Camp, Sprague. *The Great Monkey Trial.* 1968 Doubleday Inc.

Clark, R. *Einstein: His Life and Times.* 1971 World Publications.

Stern, P. *The Oppenheimer Case, Security on Trial.* 1969 Harper and Row Inc.

Joravsky, D. *The Lysenko Affair.* 1970 Harvard University Press.

science in this country. Politicians and citizens are concerned that they receive a good return on their investment in Canadian science. Canadian scientists are concerned that the result of such a committee might restrict their basic freedom to carry on investigations on the basis of individual curiosity rather than those directed towards a predetermined goal. The scientists point out that many of the major advances in science resulted from research motivated by curiosity and that the significance of many of these experiments was not realized for many years.

Although the issue of scientific freedom is of importance in any study of science, we must now return to our main theme of man's changing view of the universe. Kepler provided the geometric description of the kinematics of the solar system. Although he never singled out his three laws of planetary motion himself, they were in his texts waiting to be discovered and used. Galileo provided observational support and publicity for the Copernican system in his writings. Galileo and Kepler had not proved that the earth rotated on its axis or revolved about the sun but after Galileo's time most of the scientific community was convinced that it did.

Man's changing description of the universe followed a long and wandering evolutionary path. We started with the simple and idealistic view of the perfect celestial spheres of Plato. Modifications introduced by Ptolemy to satisfy the observed planetary motions resulted in a more complex model. Then with the suggestion of Copernicus and the laws of Kepler, both the search for simplicity of description and accuracy in prediction were satisfied. The question posed by Plato was modified and finally answered in Kepler's description of the kinematics of the solar system. The explanation for the dynamics of the solar system provided by Isaac Newton was a most brilliant leap of man's imagination. His explanation is the topic of our next chapter.

Alfred North Whitehead in his book *Science and the Modern World* described the scientific renaissance of Copernicus, Kepler, and Galileo in the following paragraph.

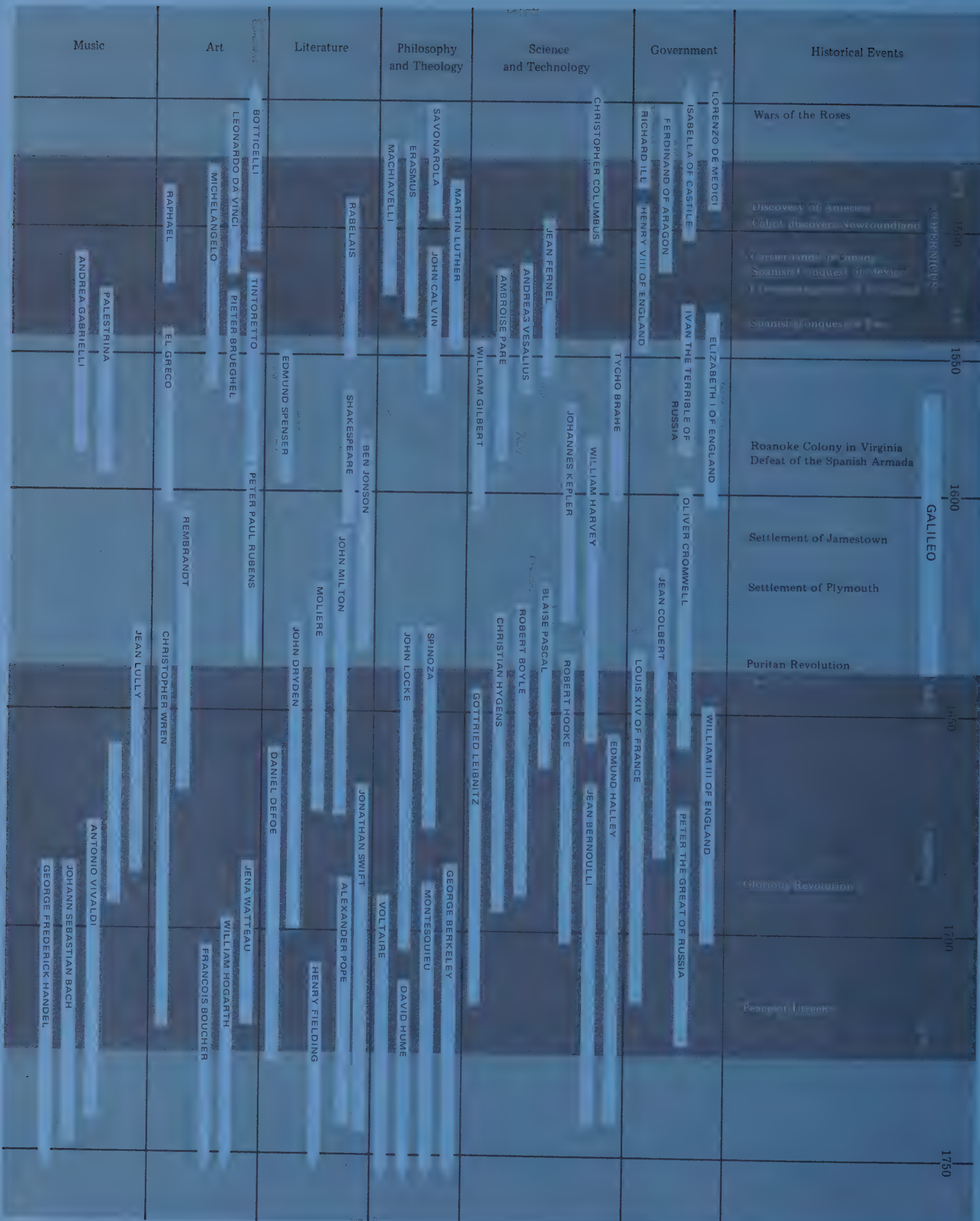
> The beginnings of the scientific movement were confined to a minority among the intellectual elite. In a generation which saw the Thirty Years' War and remembered Alva in the Netherlands, the worst that happened to men of science was that Galileo suffered an honourable detention and a mild reproof, before dying peacefully in his bed. The way in which the persecution of Galileo has been remembered is a tribute to the quiet commencement of the most intimate change in outlook which the human race had yet encountered. Since a babe was born in a manger, it may be doubted whether so great a thing has happened with so little stir.

*Q13 What is meant by freedom in scientific research?

*Q14 Discuss the implications of the following aspects of applied science and technology: germ warfare, atomic warfare, genetic engineering, unlimited access to natural resources, pollution, and other such issues which concern you.
Do these implications affect scientific freedom? Discuss.

*Q15 Summarize Galileo's contribution to the evolution of man's understanding of the universe.

See Problems 8.11 to 8.13 on page 51.



Music
Art
Literature
Philosophy and Theology
Science and Technology
Government
Historical Events
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PALESTRINA
JEAN LULLY
ANTONIO VIVALDI
JOHANN SEBASTIAN BACH
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BOTTICELLI
LEONARDO DA VINCI
MICHELANGELO
RAPHAEL
TINTORETTO
PIETER BRUEGHEL
EL GRECO
PETER PAUL RUBENS
REMBRANDT
CHRISTOPHER WREN
JENA WATTEAU
WILLIAM HOGARTH
FRANCOIS BOUCHER
RABELAIS
EDMUND SPENSER
SHAKESPEARE
BEN JONSON
JOHN MILTON
MOLIERE
JOHN DRYDEN
DANIEL DEFOE
JONATHAN SWIFT
ALEXANDER POPE
HENRY FIELDING
SAVONAROLA
ERASMUS
MACHIAVELLI
MARTIN LUTHER
JOHN CALVIN
SPINOZA
JOHN LOCKE
GEORGE BERKELEY
MONTESQUIEU
VOLTAIRE
DAVID HUME
CHRISTOPHER COLUMBUS
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GOTTRIED LEIBNITZ
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JEAN BERNOULLI
LORENZO DE MEDICI
ISABELLA OF CASTILE
FERDINAND OF ARAGON
RICHARD III
HENRY VIII OF ENGLAND
IVAN THE TERRIBLE OF RUSSIA
ELIZABETH I OF ENGLAND
OLIVER CROMWELL
JEAN COLBERT
LOUIS XIV OF FRANCE
WILLIAM III OF ENGLAND
PETER THE GREAT OF RUSSIA
Wars of the Roses
Discovery of America
Cabot discovers Newfoundland
Cartier lands in Canada
Spanish Conquest of Mexico
COPERNICUS
1500
1550
Roanoke Colony in Virginia
Defeat of the Spanish Armada
1600
GALILEO
Settlement of Jamestown
Settlement of Plymouth
Puritan Revolution
1650
Glorious Revolution
1700
Peace of Utrecht
1750

Problems Chapter 8

Section A

*8.1 Discuss the following statement. Kepler in combining the five solids of Plato, which represented the basic elements, with the distances of the planets unified the earth with the heavens.

*8.2 Using the diagrams (on page 38), explain how Kepler used Mars to determine the shape of the earth's orbit. Then explain how he determined the shape of Mars' orbit.

*8.3 How did Kepler's description of planetary motions differ from that suggested by Copernicus?

8.4 For the orbit positions nearest and farthest from the sun, a planet's speeds are inversely proportional to the distances from the sun. What is the percentage change between the earth's slowest speed in July when it is 1.02 AU from the sun, and its greatest speed in January when it is 0.98 AU from the sun?

8.5 Halley's comet has a period of 76 years, and its orbit has an eccentricity of .97.
a) What is its average distance from the sun?
b) What is its greatest distance from the sun?
c) What is its least distance from the sun?

8.6 The mean distance of the planet Pluto from the sun is 39.6 AU. What is the orbital period of Pluto?

8.7 Three new major planets have been discovered since Kepler's time. Their orbital periods and mean distances from the sun are given in the table below. Determine whether Kepler's law of periods hold for these planets also.

	Discovery Date	Orbital Period	Average Distance from Sun	Eccentricity of Orbit
Uranus	1781	84.013yr	19.19AU	0.047
Neptune	1846	164.783	30.07	0.009
Pluto	1930	248.420	39.52	0.249

8.8 In the following table are the periods and distances from Jupiter of the four large satellites, as measured by telescopic observations. Does Kepler's law of periods apply to the Jupiter system?

Satellite	Period (days)	Distance from Jupiter's Centre (in terms of Jupiter's radius, r)
1	1.77	6.04
11	3.55	9.62
111	7.15	15.3
1V	16.7	27.0

*8.9 Below are two passages from Galileo's *Letters on Sunspots.* On the basis of these quotations, comment on Galileo's characteristics as an observer and as a scientist.

(May 4th, 1612.)

I have resolved not to put anything around Saturn except what I have already observed and revealed—that is, two small stars which touch it, one to the east and one to the west, in which no alteration has ever yet been seen to take place and in which none is to be expected in the future, barring some very strange event remote from every other motion known to or even imagined by us. But as to the supposition of Apelles that Saturn sometimes is oblong and sometimes accompanied by two stars on its flanks, Your Excellency may rest assured that this results either from the imperfection of the telescope or the eye of the observer, for the shape of Saturn is thus:  as shown by perfect vision and perfect instruments, but appears thus:  , where perfection is lacking, the shape and distinction of the three stars being imperfectly seen. I, who have observed it a thousand times at different periods with an excellent instrument, can assure you that no change whatever is to be seen in it. And reason, based upon our experiences of all other stellar motions, renders us certain that none ever will be seen, for if these stars had any motion similar to those of other stars, they would long since have been separated from or conjoined with the body of Saturn, even if that movement were a thousand times slower than that of any other star which goes wandering through the heavens.

(December 1, 1612.)

About three years ago I wrote that to my great surprise I had discovered Saturn to be three-bodied; that is, it was an aggregate of three stars arranged in a straight line parallel to the ecliptic, the central star being much larger than the others. I believed them to be mutually motionless, for when I first saw them they seemed almost to touch, and they remained so for almost two years without the least change. It was reasonable to believe them to be fixed with respect to each other, since a single second of arc (a movement incomparably smaller than any other in even the largest orbs) would have become sensible in that time, either by separating or by completely uniting these stars. Hence I stopped observing Saturn for more than two years. But in the past few days I returned to it and found it to be solitary, without its customary supporting stars, and as perfectly round and sharply bounded as Jupiter. Now what can be said of this strange metamorphosis? That the two lesser stars have been consumed in the manner of the sunspots? Has Saturn devoured his children? Or was it indeed an illusion and a fraud with which the lenses of my telescope deceived me for so long—and not only me, but many others who have observed it with me? Perhaps the day has arrived when languishing hope may be revived in those who, led by the most profound reflections, once plumbed the fallacies of all my new observations and found them to be incapable of existing!

I need not say anything definite upon so strange an event; it is too recent, too unparalleled, and I am restrained by my own inadequacy and the fear of error. But for once I shall risk a little temerity; may this be pardoned by Your Excellency since I confess it to be rash, and protest that I mean not to register here as a prediction, but only as a probable conclusion. I say, then, that I believe that after the winter solstice of 1614 they may once more be observed.

(*Discoveries and Opinions of Galileo,* translated by Stillman Drake, Doubleday, 1957, pp. 101-102, 143-144.)

To Rehabilitate Galileo

The following are excerpts from a speech entitled "Religion and Natural Sciences" by Franz Cardinal Konig of Vienna at a meeting of Nobel Prize winners in Germany last week.

Neither the Christian churches nor modern science have managed to date to control that component of human nature which mirrors visibly a like phenomenon in the animal kingdom: aggressiveness. I hold that the neutralization of this instinct, which now is creating more dangers than ever before, ought to be a prime goal of objective cooperation between theologians and scientists. This work should try to bridge the incongruity between man's complete and perfected power of destruction and his psychic condition which remains unbridled and prey to atavism.

Removing Barriers

To enable such cooperation it is first of all necessary to remove the barriers of the past. Perhaps the biggest obstacle, blocking for centuries cooperation between religion and science, was the trial of Galileo.

For the church after the second Vatican Council, turning as it is to the world as an advocate of legitimate rights and the freedom of the human mind, the time appears to have come to terminate as thoroughly as possible the era of unpleasantness and distrust which began with Galileo's censure in 1633. For over 300 years the scientific world has rightly regarded as a painful, unhealing wound the church's unjust verdict on one of those men who prepared the path for modern science. Galileo's judgement is felt all the more painful today since all intelligent people inside and outside the church have come to the conclusion that the scientist Galileo was right and that his work particularly gave modern mechanics and physics a first, firm basis. His insights enabled the human mind to develop a new understanding of nature and universe, thus replacing concepts and notions inherited from antiquity.

An open and honest clarification of the Galileo case appears all the more necessary today if the church's claim to speak for truth, justice, and freedom is not to suffer in credibility and if those people are not to lose faith in the church who in past and present have defended freedom and the right to independent thought against various forms of totalitarianism and the so-called raison d'état.

I am in a position to announce before this meeting that competent authorities have already initiated steps to bring the Galileo case a clear and open solution.

The Catholic Church is undoubtedly ready today to subject the judgement in the Galileo trial to a revision. Clarification of the questions which at Galileo's time were still clouded allow the church today to resume the case with full confidence in itself and without prejudice. Faithful minds have struggled for truth under pain and gradually found the right way through experience and discussions conducted with passion.

The church has learned to treat science with frankness and respect. It now knows that harmony is possible between modern man's scientific thinking and religion. The seeming contradiction between the Copernican system or, more precisely, the initial mechanics of modern physics and the biblical story of creation has gradually disappeared. Theology now differentiates more sharply between essentially divine revelations, philosophical constructions and spontaneously naive views of reality.

What used to be insurmountable obstacles for Galileo's contemporaries have stopped long ago to irritate today's educated faithful. From their perspective Galileo no longer appears as a mere founder of a new science but also as a prominent proponent of religious thinking. In this field, too, Galileo was in many respects a model pioneer.

Trial and Error

In Galileo's wake and in the spirit of his endeavours the Catholic church has through trial and error come to recognize the possibility of harmonious cooperation between free research and free thinking on the one hand and absolute loyalty to God's word on the other. Today's task is to draw the consequences from this recognition. Without fixing borders, God has opened his creation—the universe—to man's inquiring mind.

The church has no reason whatsoever to shun a revision of the disputed Galileo verdict. To the contrary, the case provides the church with an opportunity to explain its claim to infallibility in its realm and to define its limits. However, it will also be a chance to prove that the church values justice higher than prestige.

New York Times, July 1968.

8.10 Does the planet Jupiter exhibit phases when viewed from the earth?

8.11 What are the current procedures by which the public is informed of new scientific theories? Do you think they are adequate? To what extent do news media emphasize clashes of points of view?

8.12 Recently the Roman Catholic Church decided to reconsider its condemnation of Galileo. The article reproduced opposite, which appeared in *The New York Times*, July 1968, quotes passages from an Austrian Cardinal's view of the question.

a) In the quoted remarks Cardinal Konig lists three forms of knowledge: "divine revelations", "philosophical constructions", and "spontaneously naive views of reality". Under which of these do you think he would classify Galileo's claims? Would Galileo agree?

b) What seems to be the basis for the reconsideration? Is it doubt about the *conclusions* of the trial, or about the *appropriateness* of trying scientific ideas at all? Is it being reconsidered because of a change in Church philosophy, or because Galileo turned out to be right?

*8.13 Why did kings spend so much money in supporting astronomers like Galileo, Kepler, and Brahe?

Section B

*8.14 Re-read the arguments for and against the Copernican system presented in Chapter 7. How have these been changed by the work of Galileo and Kepler?

*8.15 The view we have of a scientist depends upon his biographer. Compare the view of Galileo presented by Arthur Koestler in *The Sleepwalkers* with that of Stillman Drake presented in *Discoveries and Opinions of Galileo.*

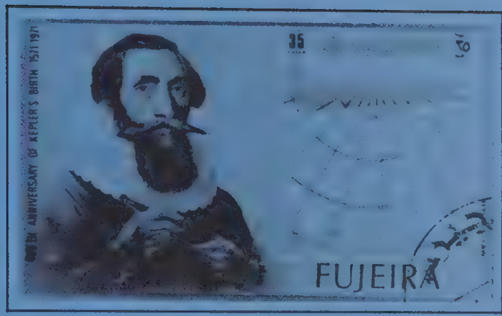
Feb. 19, 1473	Born at Torun, Poland
1491	Entered University at Cracow
1496	Continued education at Bologna
1497	Appointed Canon of Cathedral of Frauenburg
1503	Completed doctorate in canon law
1501-1505	Studied at Medical School in Padua
1506	Started to develop his astronomical system
1512	Assumed residency at Frauenburg
1514	Invited to assist in calendar reform
1522	Presented scheme for currency reform
May 24, 1543	Received advance copy of *De Revolutionibus* and died.

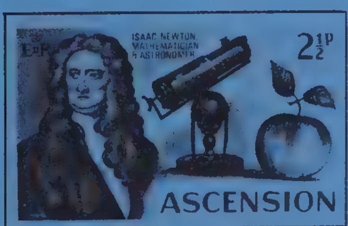
GALILEO

Feb. 15, 1564	Born at Pisa, Italy
1575	Early education at Florence
1581	Matriculation at University of Pisa
1583	Discovered uniformity of pendulum
1589	Taught at University of Pisa
1592	Appointed professor of mathematics at Padua
1602	Experimented with magnetism
1604	Law of falling bodies
1609	Constructed a telescope
1610	Published *Sidereus Nuncius*
1612	Published book on floating bodies
1613	Published *Letters on Sunspots*
1616	Copernican theory condemned and Galileo forced to abandon it
1624	Modified compound microscope
1632	Published *Dialogues Concerning Two Chief World Systems* (Italian Version)
1633	Examined by Inquisition, placed under house arrest
1635	*Dialogue* published in Latin
1638	Published *Two New Sciences*
Jan. 8, 1642	Death of Galileo.

KEPLER

Dec. 27, 1571	Born at Weil Germany
1584	Sent to Adalberg as charity student
1588	Received bachelor degree and went to University of Tubergen for further study
1594	Accepted chair of astronomy at Lutheran school at Graz
1596	Published *Mysterium Cosmograrphicum*
1600	Accepted post with Tycho Brahe
1601	Became "Imperial Mathematician" following Brahe's death
1602	Published *On the More Certain Foundation of Astrology*
1604	Published *Optical Part of Astronomy* (preliminary study on optics)
1609	Published *Astronomia Nova*
1611	Published *Dioptrices*
1619	Published *Harmonics of the World*
1627	Published *Rudolphine Tables*
Nov. 15, 1630	Death of Kepler.





NEWTON

Dec. 25, 1642	Born at Woolsthorpe, England
1661	Matriculated at Trinity College, Cambridge
1665	University closed because of plague, returns to Woolsthorpe
1666	Newton at Woolsthorpe — developed integral calculus — composition of white light — early ideas of gravitational force
1667	Elected as fellow at Cambridge
1668	Accepted chair of mathematics from Isaac Barrow
1669	Presentation of telescope to Royal Society and election as fellow
1672	Presented treatise on light to Royal Society
1675	Carried out experiments in alchemy
1684	Began writing of *Principia*
1687	First edition of *Principia* published
1689	Elected to parliament for the university
1692	Nervous breakdown
1695	Appointed Warden of the Mint
1699	Appointed Master of the Mint
1703	Elected President of Royal Society
1704	Publication of *Opticks*
1705	Received knighthood
Mar. 20, 1727	Newton's death and burial in Westminster Abbey.

Chapter 9 *The Unity of Earth and Sky*
The Work of Newton

The Unity of Earth and Sky
The Work of Newton

Chapter Nine

"If I have seen further (than others) it is by standing on the shoulders of giants."

Isaac Newton

The quotation above was taken from a letter written by Isaac Newton to Robert Hooke. It refers to a legend involving a dwarf with very keen eyes who assisted some giants who lacked his powers of visual perception. In this statement Newton both acknowledges the contribution made by the great men before him and recognizes his own powers.

Robert Hooke: (1635-1703), British physicist who was to disagree with many of Newton's ideas.

9.1 Isaac Newton: A Brief Biography

Isaac Newton was born on Christmas Day 1642. He does not seem to have been an exceptional child. At the age of 19 he enrolled at Cambridge University and graduated three years later. His interest and ability in mathematics was recognized and cultivated by the mathematics professor, Isaac Barrow, who in 1668 resigned from his professorship in mathematics so that Newton might have it.

If you are interested in a complete biography of Newton, consult L. T. More's *Newton, a biography:* Dover Books.

Newton's studies at Cambridge were interrupted in 1665 when he returned to his childhood home in Woolsthorpe. Cambridge was closed for nearly two years because of the great plague. It was during these years at Woolsthorpe that Newton developed the foundation on which his contributions to science were built. In this relatively short time he developed several major theorems in mathematics including those of the differential calculus; he performed a series of experiments in optics, the most famous of which showed the composite nature of white light; and he began the initial development of the concept of universal gravitation.

Newton's home at Woolsthorpe.

Newton seemed to be able to bring to a problem an enormous power of concentration. He would work for days without rest until he was satisfied with his solution. Perhaps when relaxing in the garden after such a bout of concentrated effort Newton arrived at the idea that the same force which causes an apple to fall to the earth holds the planets in their orbit. Twentieth century scientists tell stories of arriving at the answer to a difficult problem while playing golf or listening to music after having worked on the problem for days without any apparent progress. A modern scientist usually hurries his ideas to publication. Newton, however, seemed to lack the desire to publish and some of the ideas initiated in the garden and cottage at Woolsthorpe were not further developed or published until forty years later. Newton returned to a Fellowship at Cambridge where he did more research and some lecturing. He gave about eight lectures each year on his original research.

Academies of Science were also founded in Florence and Paris. Today, in addition to these societies, we have large international organizations which publish papers and organize meetings for the exchange of ideas.

During Newton's youth the Royal Society was founded in London. This scientific society was able to support some scientific work but, most important, it permitted and encouraged the presentation, discussion, and publication of new scientific ideas. In 1671, Isaac Newton presented to the Royal Society a reflecting telescope which he had invented and built. In recognition he was elected a Fellow of the Society. Encouraged by the Society, he presented a scientific paper outlining some of his experiments in optics. This work,which indicated Newton's ability as an experimenter, was regarded as a model of a scientific paper. It is described by Professor L. T. More, a biographer of Newton:

> In form, the article is a work of art—clear, concise, and admirably arranged to lead the reader from a dramatic introduction straight to a convincing conclusion. He, certainly, made many observations which must have been useless; but from his notes he selected those which were pertinent and forbore to weary and confuse his readers by giving a mass of irrelevant details. That is, contrary to custom, he relied on a few carefully selected experiments to prove his thesis.

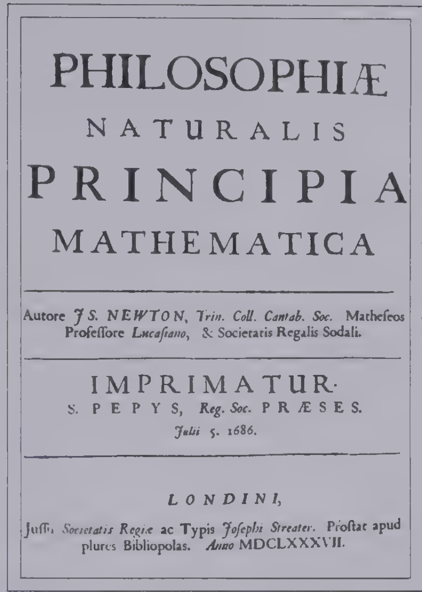
What a contrast to the style of Kepler! Although Newton's paper was a model in format, many scientists had their own theories which in some cases conflicted with the ideas of Newton. This resulted in much discussion and debate. Probably the controversy caused by this paper and a later one in which Newton considered light to be streams of small corpuscles, was the reason that Newton ceased to publish and turned to other interests for over ten years.

A translation of Newton's *Optics* is published by Dover Press.

His major work on light, *Opticks*, was not published until 1704, 33 years later. This was the year following the death of Robert Hooke who was one of Newton's strongest critics. Although the work on optics was one of Newton's major contributions to physics, in this section we are more concerned with his ideas on astronomy. In 1684 several of the members of the Royal Society were concerned with the following question: What is the nature of the force that causes the planets to move in the manner indicated by Kepler's laws? At the suggestion of the other members, Edmund Halley went to Cambridge to ask Newton his opinion. Upon his arrival he found that Newton had solved this problem some years before but had misplaced the

calculations. Most of Europe was searching for a law of gravitation and Newton had already found it and lost it!

Encouraged by Halley, Newton repeated the calculations and also solved many related problems. Newton used this work in his lecture course at Cambridge in 1684 and 1685. Out of these lectures grew the most famous book in the history of science, the *Mathematical Principles of Natural Philosophy*, referred to as the *Principia*, and published by the Royal Society in 1687. The text is very difficult to read because it involves many detailed geometrical proofs, but it has become famous through many popularizations. Publication of the *Principia* and *Opticks* established Newton as one of the greatest thinkers in history.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

Autore *J S. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Title page of Newton's *Principia Mathematica*. Because the Royal Society sponsored the book, the title page includes the name of the Society's president, Samuel Pepys, famous for his diary, which describes life during the seventeenth century.

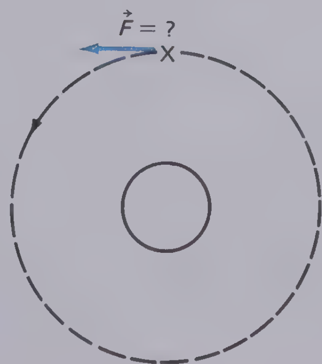
Several years afterwards Newton had a nervous breakdown. He recovered, but from then until his death, thirty-five years later, he made no major scientific discoveries. He rounded out earlier studies on heat and optics and turned more and more to writing on theology. During those years he received many honours. In 1699 he was appointed Warden of the Mint and subsequently its Master, partly because of his great interest in and knowledge about the chemistry of metals. In that office he helped to re-establish the value of British coins in which lead and copper were being included in place of silver and gold. In 1689 and 1701 he represented Cambridge University in Parliament and was knighted in 1705 by Queen Anne. He was president of the Royal Society from 1703 until his death in 1727. He was buried in Westminster Abbey.

Alexander Pope commemorated Newton with the following epigram:

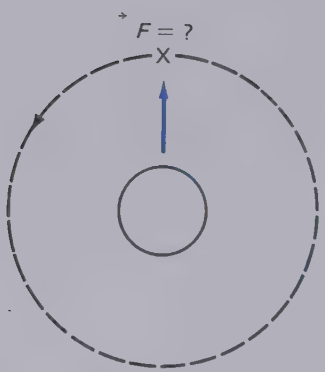
> Nature and Nature's laws lay hid in night.
> God said, "Let Newton be!" and all was light.

9.2 What Makes the Planets Go Around?

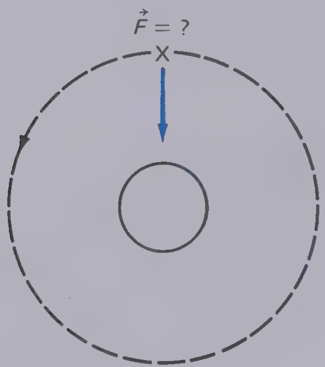
Whether we are Aristotelian or Copernican in our view of the solar system, we seek to explain the dynamics of the regular motion of the planets in the sky. The Greek explanation introduced the transparent celestial spheres which carried the stars and planets on their circular paths. Circular motion was seen as the natural state for these objects and further explanations were neither sought nor required. This problem was to be reconsidered in the sixteenth and seventeenth centuries and several explanations proposed. Kepler suggested that a magnetic field emanating from the sun carried the planets around in their orbits. This force, Kepler said, decreased with increasing distance from the sun, resulting in the more distant planets revolving with less speed. René Descartes described interplanetary space as being filled with moving matter of a nonperceivable type. Vortices and currents in this nonperceivable matter, *aether*, carried the planets in their orbits. Kepler and Descartes were attempting to explain what made the planets move. Their search was directed to finding some force that would push the planets around in their orbits.



What pushes it around?



What holds it up there?



What holds it down?

Eventually, with the gain in popularity of the notion of the heaviness of celestial objects and the idea that the moon was attracted to the earth, the question became: "What keeps these objects in orbit and prevents them from falling toward the earth or sun?" In 1660 Giovanni Borelli, an Italian astronomer, suggested that the tendency of a planet to approach the sun was exactly balanced by its tendency to fly out due to its circular motion. He also stated that the force pushing the planets around in their orbits was the push of the light being emitted by the sun. Even today many people ask the question: "What holds the earth satellites "out there"?"

Following the introduction of the concept of inertia and the idea that linear motion at a constant speed was "natural", the question became: "Why do the planets not fly off from the sun in a straight line?" This produced another modification to the question of the dynamics of planetary motion. It was changed from "What holds the planet up there?" to "What holds it down and prevents it from flying off into space?" It was this question which Newton faced. It is important to realize that until the correct questions were formulated satisfactory theories could not evolve.

*Q1 How did the question concerning the force that makes the planets go around change with time?

*Q2 Why is the question "What keeps an earth satellite out there?" not the best question to ask concerning orbiting satellites?

9.3 The Law of Universal Gravitation

a) *The Dependence on Distance*

Kepler's laws provide a good description of the *kinematics* of the system.

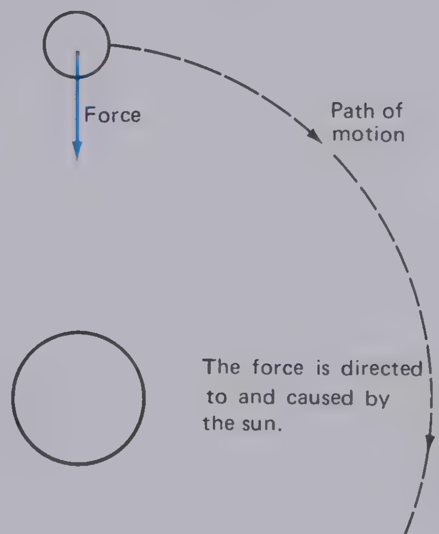
Newton's explanation of the dynamics of the solar system was a single simple mathematical expression, which is now known as *The Law of Universal Gravitation.* In developing this law Newton combined his laws of motion, which we have studied in Unit 1, with Kepler's three laws. To do this, he decided that both terrestrial and celestial bodies must obey the same physical laws. This step in his reasoning was a most significant leap of the imagination. Legend has it that this decision was made in the garden at Woolsthorpe while Newton was watching a falling apple. On this occasion Newton perceived that the same force of gravity which pulled the apple toward the centre of the earth could be responsible for holding the moon and planets in their orbits. Others had proposed the existence of a force of attraction between the sun and the planets, but until Newton, none had suggested that there was a similarity between this force and the gravitational force that affected objects on earth. Newton believed that this force would probably extend throughout the universe. No longer was Newton's search limited to finding a mechanism which might cause the planets to revolve. He had studied the mechanisms proposed by Kepler and Descartes, and found them

René Descartes: (1596-1650) French philosopher and mathematician.

unsatisfactory. He was now seeking to explain the nature of this force called gravity. Let us examine some of the work which led to its understanding.

The realization that the force of gravity might spread throughout the universe has been called "the greatest extrapolation of the human mind".

1. One of Newton's first steps in the analysis was to determine the direction in which the force of gravity acts on a planet. His first Law of Motion states that an object will remain in a state of rest or travel at constant speed, in a straight line unless acted on by an external force. Since the planets were not travelling in a straight line, there must be an external force causing them to accelerate by changing their speed and direction of motion. Newton showed that since the planets obeyed Kepler's Law of Areas this force must be directed to a single point in space and that this point was at the location of the sun. Newton saw the sun not only as the point to which the force was directed, but also as **the cause of the force.**



The force is directed to and caused by the sun.

2. If the orbits of the planets are assumed to be circular it is possible to prove that the centrally directed acceleration of the planets decreases with the square of their distance from the sun. This motion satisfies Kepler's Law of Periods. Newton, however, satisfied this law for the more difficult and observed situation of planets travelling in ellipses. Since the acceleration decreases in proportion to the square of the distance and, by Newton's Second Law of Motion acceleration is proportional to net force, Newton concluded that the force of gravity, $F_{gravity}$, must decrease in proportion to the square of the distance from planet to sun, R

$$F_{gravity} \propto \frac{1}{R^2}.$$

3. This expression offers an opportunity to do a most interesting calculation that was first done by Newton. He used this expression to calculate the acceleration of the moon toward earth knowing the acceleration of an apple. The moon is at a distance of about 60 earth-radii, hence it is about 60 times farther from the centre of the earth than the apple is. The gravitational force on the moon would be $(1/60)^2$ of the force on the apple. Therefore, since the acceleration of the apple is equal to 9.8 metres per second per second, the *predicted* acceleration of the moon is,

$$\begin{aligned} \text{acceleration of moon} &= 9.8\ \text{m/s}^2 \times \left(\frac{1}{60}\right)^2 \\ &= 9.8 \times \frac{1}{3600}\ \text{m/s}^2. \\ &= 2.72 \times 10^{-3}\ \text{m/s}^2. \end{aligned}$$

The formula for the acceleration of an object in uniform circular motion is derived on page 62 .

Average radius of moon's orbit is 3.8×10^8 metres.

Period of moon's revolution is 2.36×10^6 seconds.

The *observed* acceleration of the moon using the formula for acceleration of an object travelling in a circle at constant speed is

$$a_{moon} = 2.74 \times 10^{-3}\ \mathrm{m/s^2}.$$

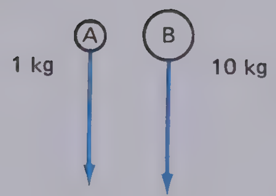
(This of course is an approximation because the moon's path is slightly elliptical.) These values are remarkably similar and reinforce the theory that the force on the apple is in fact extended into space.

In doing this calculation we have assumed that the force acting on the apple is measured from the centre of the earth. This is by no means an obvious assumption, however, Newton showed that the gravitational attraction of the matter making up a uniform sphere may be calculated by considering all the mass to be concentrated at a central point.

Q3 State the effect (on the gravitational force of attraction exerted by the earth on the moon) of the following changes in the earth-moon distance.

a) The separation doubles.
b) The separation triples.
c) The separation decreases to one-half its present value.
d) The separation decreases to one-third.

See also 9.1 to 9.3 on page 78.



b) *The Dependence on Mass*

Acceleration due to gravity is $9.8\ \mathrm{m/s^2}$.

Since *A* and *B* have the same acceleration and the mass of *B* is ten times the mass of *A*, we must conclude that force on *B* is ten times as great as the force on *A*.

The other quantity which determines the magnitude of the gravitational force between objects is their masses. It is interesting to consider the consequences of applying Newton's Third Law to gravitational force. The Third Law implies that not only does the earth exert a downward force on the apple, but that the apple exerts an equal and opposite force on the earth. However, Newton's Third Law does not operate in isolation and his Second Law, net force is proportional to acceleration, must be considered. We would expect this force to produce a much smaller acceleration in the earth than in the apple since the earth is approximately 10^{24} times more massive.

We have observed that all objects near the earth fall with the same acceleration due to gravity. Consider a one kilogram mass, *A*, and a ten kilogram mass, *B*, falling freely near the earth with an acceleration of 9.8 metres per second per second. *B* has ten times the mass of *A* but the same acceleration. Therefore we must conclude, after considering Newton's Second Law, that the force acting on *B* is ten times as great as the force acting on *A*.

Thus, if an object has a large mass not only does it have a large inertia opposing acceleration, but it is more strongly attracted to the earth by gravitational force. This relationship between inertia and gravitational attraction explains Galileo's observation of the common acceleration for all freely falling objects near the surface of the earth.

We must then conclude that the force of attraction between the earth and an object is proportional to the mass of the object. Also, since the force of the earth on the object is equal to the force of the object on the earth, we must further conclude that the force of attraction is proportional to both the mass of the earth and the mass of the object. That is, the force is proportional to the product of their masses.

$$Force_{gravity} \propto mass_{earth} \times mass_{object}$$

$$F_g \propto m_e \cdot m_o$$

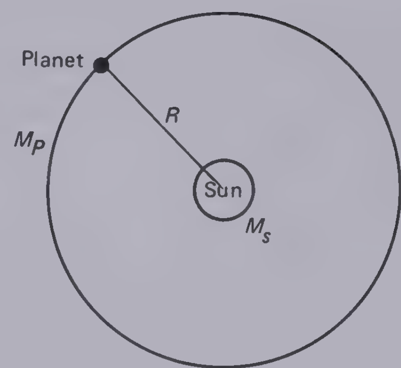
Q4 State the effect of the following changes in mass on the gravitational force of attraction between two objects. (There is no change in the separation of the objects.)
a) The mass of one object doubles.
b) The mass of one object triples.
c) The mass of one object is reduced to one-half its original value.
d) The mass of one object doubles and the mass of the other triples.

Q5 The earth is about 80 times as massive as the moon. How does the gravitational force exerted by the earth on the moon compare with that exerted by the moon on the earth?

See problem 9.4 on page 78.

c) *The Universal Law*

Newton believed that this gravitational force was the force that Kepler had sought when he wanted to explain the motion of the planets. The force of gravitational attraction between a planet and the sun is proportional to the product of the mass of the planet and the mass of the sun. In addition, the gravitational force decreases in proportion to the square of the distance between the sun and planet. These two relationships are combined in the single expression:



$$Force_{gravity} \propto \frac{mass_{planet} \times mass_{sun}}{(distance\ between\ centres)^2}$$

$$F_g \propto \frac{m_p \times m_s}{R^2}$$

F_g represents the gravitational attraction between the planet and the sun.
R represents the distance between the centre of the sun and the centre of the planet.

The expression of proportionality may be written as an equation by introducing a constant, the value of which depends upon the units used. The symbol used for this constant in the equation representing the Law of Universal Gravitation is G.

$$F_g = G \frac{m_p \cdot m_s}{R^2}$$

This equation is a bold assertion that the force between the sun and any planet depends only upon the masses of the sun and planet and the distance between them. This equation seems

Consider an object travelling at constant speed counterclockwise in a circular path of radius R. If the object makes one revolution in time T, the speed of the object is,

$$v = \frac{\Delta x}{\Delta t} = \frac{2\pi R}{T}.$$

We have shown the velocity vectors for four positions in Fig. 1. The length of these vectors represents the *speed* of the object, $v=2\pi R/T$, and the direction of the vector shows the *direction* in which the object is travelling. As the object travels around the circle, the direction of the velocity vector rotates counterclockwise.

We could imagine the velocity vector as sweeping out a circle of radius v during each period of revolution, and use it to determine a value for the acceleration. Because the velocity vector swings around a circle of radius, v, the change in velocity, Δv, in time, T, is $2\pi v$.

Therefore the magnitude of this centripetal acceleration, a_c, is:

$$a_c = \frac{\Delta v}{\Delta t} = \frac{2\pi v}{T}.$$

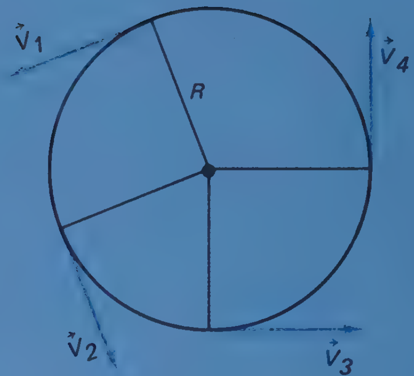


Fig. 1

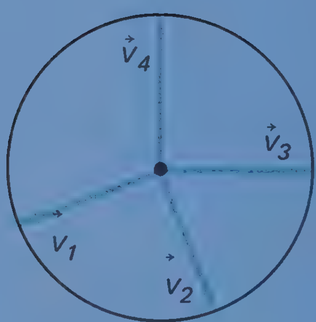


Fig. 2

It can be shown that the acceleration is directed toward the centre of the circle.

Note also that *Newton's Second Law* is used here to apply to celestial objects, although it was originally stated for objects on the earth.

Since, $\quad a_c = \frac{2\pi v}{T}$ and $v = \frac{2\pi R}{T}$,

therefore, $\quad a_c = \frac{2\pi}{T} \cdot \frac{(2\pi R)}{T}$,

$$a_{centripetal} = \frac{4\pi^2 R}{T^2}.$$

Also, $\quad a_c = \frac{2\pi v}{T}$ and $\frac{2\pi}{T} = \frac{v}{R}$

then, $\quad a_c = \frac{v}{R} \cdot v$

or, $\quad a_{centripetal} = \frac{v^2}{R}.$

Both these forms are useful in the calculation of acceleration.

A more rigorous proof using calculus proves that these expressions represent the magnitude of the acceleration at all points on the path.

According to Newton's Second Law, an accelerated object on the earth must be acted upon by a force, the magnitude of which is given by the equation,

$$F = ma$$

In addition to this application, Newton went even further and proposed that the same law should also apply to celestial objects. For a body moving in a circular orbit, for example a planet, there would be a force acting in the same direction as the acceleration. The magnitude of this centripetal force F_c, would be

$$F_c = ma_c.$$

Using the expressions derived above,

$$F_c = \frac{4\pi^2 mR}{T^2}$$

or, $$F_{\text{centripetal}} = \frac{mv^2}{R}.$$

Centripetal force is examined in Experiment 9.1, *Centripetal Force*, pg. [illegible].

[illegible]

For planets travelling in a circular orbit the magnitude of acceleration is given by the expression.

$$a_c = \frac{4\pi^2 R}{T^2},$$

where R represents the radius of the orbit, and T represents the period of revolution.

From Kepler's *Law of Periods* we know that the relationship between the period and the radius of orbit may be expressed as,

$$\frac{T^2}{R^3} = \text{a constant, say } k.$$

Therefore, $$T^2 = kR^3.$$

If we now substitute kR^3 for T^2 in the acceleration equation, we obtain

$$a_c = \frac{4\pi^2 R}{kR^3}.$$

Since $\frac{4\pi^2}{k}$ is itself a constant,

then $$a_c \propto \frac{1}{R^2}.$$

and by Newton's Second Law,

$$F_c \propto a.$$

Therefore $$F_c \propto \frac{1}{R^2}.$$

Thus we have shown that the inverse square force of attraction is a condition for Kepler's *Law of Periods* for circular planetary motion.

unbelievably simple when we remember the observed complexity of the planetary motions. Yet one of Kepler's Laws of Planetary Motion is consistent with this relation. More than that, Kepler's empirical laws can be derived from this force law together with Newton's Second Law of Motion. But more important still, the force law allowed the calculation of details of planetary motion that were not possible using only Kepler's laws.

Newton's proposal, that such a simple equation describes completely the forces acting between the sun and planets, was not the final step. He believed that there was nothing unique or special about the mutual force acting between the sun and planets, or between the earth and an apple, but that an identical relation should apply universally to *any two bodies* separated by a distance that is large compared to the dimensions of the two bodies—even to two atoms or two stars. That is, he proposed that we can write a general *Law of Universal Gravitation:*

$$F_{grav} = G\frac{m_1 m_2}{R^2}$$

where m_1 and m_2 are the masses of the bodies and R is the distance between their centres. The numerical constant G, called the *constant of universal gravitation*, Newton assumed to be the same for all gravitational interaction, whether between grains of sand, two members of a solar system, or two stars in different parts of the sky. As we shall see, the successes made possible by this simple relationship have been so great that we have come to assume that this equation applies everywhere and at all times, past, present, and future.

Even before we gather more supporting evidence, the sweeping majesty of Newton's theory of universal gravitation commands our wonder and admiration. It also leads to the question of how such a bold universal theory can be proved. There is no complete proof, of course, for that would mean examining every interaction between all bodies in the universe! But the greater the variety of single tests we make, the greater will be our belief in the correctness of the theory.

*Q6 Summarize the steps Newton used in arriving at his Universal Law of Gravitation as outlined in this section.

Q7 Did Newton explain gravitational attraction?

Q8 Explain the effect of each of the following changes on the force of attraction between two objects.

a) The distance between the objects doubles.

b) The mass of one object is reduced to one-half and the distance between objects doubles.

c) The mass of one object doubles, the mass of the other object triples and the distance between is decreased by one-half.

See problem 9.5 on page 78.

9.4 Determination of the Gravitational Constant: G

Before we can use the equation $F_g = G\frac{m_1\, m_2}{R^2}$ to calculate the actual force of gravitational attraction between two objects we must determine a value for the constant G. A direct method of doing this would be to take two objects and by some means measure the force of gravitational attraction between them. Then, knowing their masses and distance of separation, we could substitute values of F, m_1, m_2, and R into the equation and solve it for G. This experiment is most difficult to perform because the gravitational force between most objects is very small and difficult to measure. Newton calculated an approximate value for G by considering the force of attraction between the earth and an object on its surface. He solved the gravitational equation in the following form:

$$G = \frac{F_g R^2 e}{m_o\, m_e}$$

F_g is the weight of the object.

R_e, radius of the earth, was known to Newton from the measurements of surveyors.

m_e was estimated by Newton using the density of surface matter.

m_o is easily obtained. (Value of the mass of the object.) Using this method and Newton's values we can obtain a value for G of $6 \times 10^{-11} \frac{\text{N} - \text{m}^2}{\text{kg}^2}$.

More recent experiments using a more direct method establish a value of $6.67 \times 10^{-11} \frac{\text{N} - \text{m}^2}{\text{kg}^2}$.

Let us use this value of G to perform a calculation of the force of gravitational attraction between two objects.

Problem: To determine the gravitational force of attraction between an object of mass 50 kg and an object of mass 70 kg at a separation of one metre.

Solution: Using the gravitational equation,

$$F_g = \text{G}\frac{m_1\ m_2}{R^2}$$

$$= \frac{6.67 \times 10^{-11}\ \frac{\text{N-m}^2}{\text{kg}^2} \times 50\text{kg} \times 70\text{kg}}{1\text{m}^2}$$

$$= 2.33 \times 10^{-7}\ \text{newtons.}$$

Q9 Why is it difficult to determine a value of the gravitational constant directly?

Q10 Using the information in the chart at the end of this unit determine

a) the gravitational force exerted by the earth on the moon. How does this compare with the force exerted by the moon on the earth?

b) the gravitational force exerted by the sun on the moon. How does this compare with the force exerted by the moon on the sun?

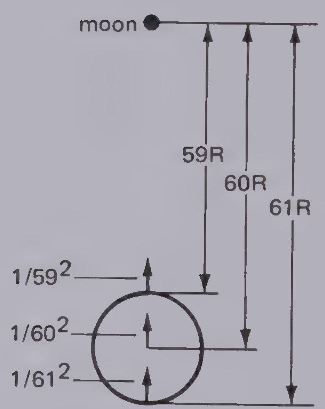
Then compare your answers.

See problems 9.6 to 9.9 on page 78.

9.5 Dividends from the Law of Gravity

Masses Compared to Earth	
Earth	1
Saturn	95
Jupiter	318
Sun	333,000

Earth-Sun Distances:	1972
Aphelion:	152,105,960 km
Perihelion:	147,088,505 km
Mean Distance:	1.496×10^8 km



Tidal Forces.

The earth-moon distance indicated in the figure is greatly reduced because of space limitations.

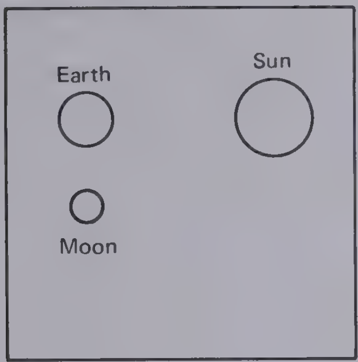
Newton's contribution to astronomy did not end with his mathematical description of the force of gravity. He used this law to calculate the masses of some of the bodies in the solar system and used the concept of universal gravitation to explain the phenomena of tides and comets. In this section we shall briefly examine some of the benefits which came from an understanding of gravity.

Masses of objects in the solar system: Using his equation for the force of gravity, Newton was able to calculate the masses of the sun and those planets which had moons, in terms of the mass of the earth. In order to determine the actual masses, it was necessary to have a value of G. Newton realized his value of G was only an approximation and did not use it in these calculations. The calculation of the masses of these objects, at a distance of several million miles, was an impressive achievement.

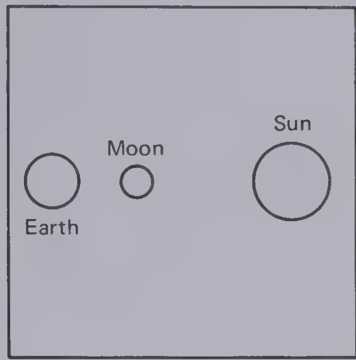
Tides: Early explanations of the ocean tides involved either vortices or forces due to the rotation of the earth. Newton explained that tides were a result of the force of gravity of the moon, and to a lesser extent of the sun, on the oceans of the earth. The gravitational force of the moon caused a tidal bulge in the oceans as the earth made its daily rotation. But anyone who has spent time near the sea is aware that there are two high tides each day not just one, as you might expect by considering the rotation of the earth beneath the moon. This can be explained if we consider the diagram opposite.

The gravitational force of the moon on the earth is greatest at point A (since this is the closest point to the moon) creating a tidal bulge on the ocean there. However, the force on the earth at B is greater than that on the ocean at C. This results in the earth being pulled toward the moon at a greater rate than the oceans at point C and causes a tidal bulge at C. Thus, we get two high tides because, at the side of the earth beneath the moon, the oceans are pulled from the earth, and on the side of the earth opposite the moon, the earth is pulled away from the oceans. The time of high tide is somewhat later than the time when the moon is directly overhead because of the effects of inertia and friction.

The relative positions of the sun and the moon determine variations in the height of the high tides. This is illustrated in the diagrams below.



Condition for lower high tide. Gravitational pull of the sun and moon tend to cancel each other. This is called a *neap tide.*



Condition for very high tide. Note how the gravitational pull of the sun and moon are reinforcing each other. This is called a *spring tide.*

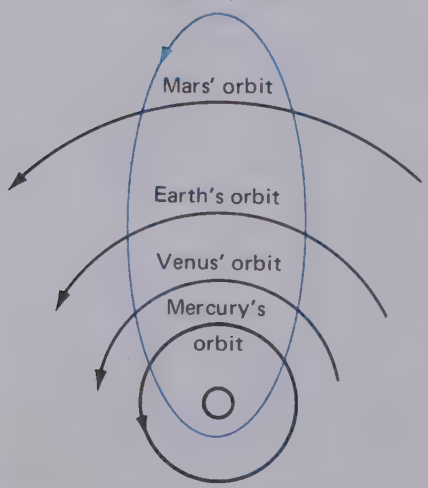
Low tide at the Bay of Fundy, Parrsboro, Nova Scotia.

High tide at the Bay of Fundy, Parrsboro, Nova Scotia.

Newton used the differences in measurements of heights of high tides to estimate the mass of the moon in terms of the mass of the sun. Newton also explained that seasonal variations in tides were caused by variations in the distance from earth to sun.

Tidal effects are not restricted to the oceans of the earth, the atmosphere of the earth also rises and falls. In fact, even the "rigid" earth itself bends regularly as a result of "tidal forces". Recent analysis of the data from the seismographs left on the moon as part of the Apollo program, show that the rocks of the moon shift regularly. These small moonquakes are lunar tides in the moon's mantle caused by the gravitational force of the earth.

LOCATION	HEIGHT ABOVE DATUM OF SOUNDINGS									
	LARGE TIDES				AVERAGE TIDES				Mean Water Level	
	Higher H.W.		Lower L.W.		Higher H.W.		Lower L.W.			
	feet	metres	feet	metres	feet	metres	feet	metres	feet	metres
Saint John	29.1	8.9	0.4	0.1	25.1	7.6	3.6	1.1	14.3	4.4
Partridge Island	28.7	8.7	0.1	0.0	24.7	7.5	3.3	1.0	14.0	4.3



Schematic diagram of the orbit of a comet projected into the ecliptic plane; comet orbits are tilted at all angles.

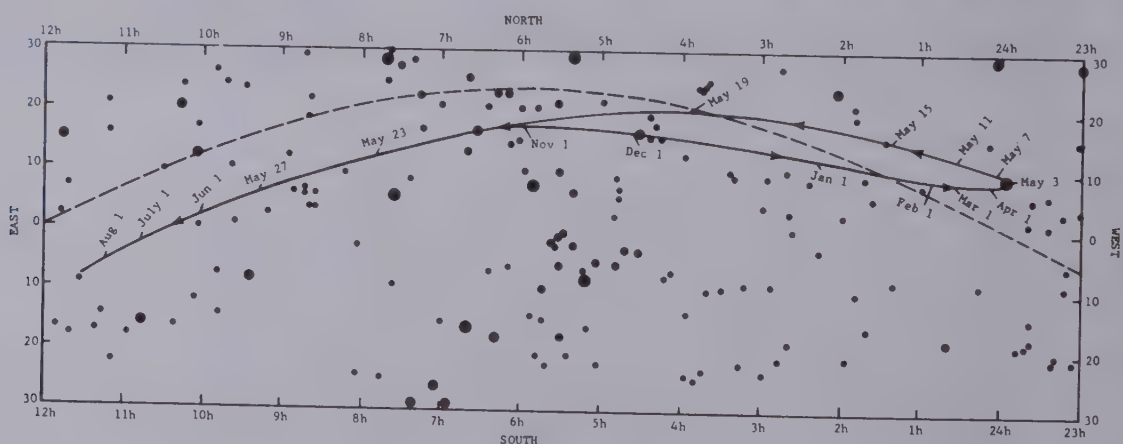
You can develop an understanding of the motion of Halley's comet by trying Activity 9.4, pg. 145.

Comets: Newton's explanation for the appearance of comets removed much of the mysticism associated with these objects whose irregular appearance was often interpreted as heralding a global disaster. Newton applied his concepts of celestial motion to show that these objects were members of the solar system in very eccentric elliptical orbits. Many of these orbits passed between Mercury and the sun. However these orbits, unlike those of the planets, were not confined to the ecliptic plane but were tilted at any angle.

Newton believed that the comet's tails, which grow in size and brightness as the comet approaches the sun, were gases at very low pressure. In the following passage from the *Principia*, he explains how a small amount of gas might fill a large volume.

> . . . "that a sphere of that air which is nearest to the earth of but one inch in diameter, if dilated with that rarefaction which it would have at the height of one semidiameter of the earth, would fill all the planetary regions as far as the sphere of Saturn, and a great way beyond and at the height of ten semidiameters of the earth would fill up more space than is contained in the whole heavens on this side the fixed stars.

Edmund Halley was able to use Newton's explanation and the records of previous observations of comets to show that many comets recurred at regular intervals. He predicted the reappearance in 1757 of the major comet which now bears his name. This comet, which has an orbital period of about 75 years, reappeared in 1833 and 1909 and should pass near the sun again in 1986.

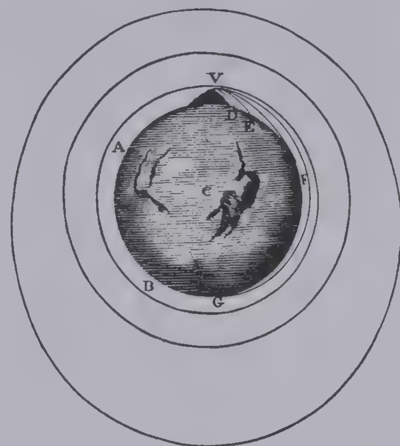


Observed motion of Halley's comet during 1909-1910. It is predicted that Halley's comet will arrive at the perihelion point of its orbit on April 29, 1986.

Artificial satellites: Probably Isaac Newton did not anticipate that the space surrounding the earth would in the twentieth century start to become cluttered with orbiting scientific apparatus and debris as a result if man's entry into nearby space. However, he did indicate in the *Principia* that any projectile launched from the earth is in effect an earth satellite. His sketch opposite shows various orbital shapes which depend upon the speed with which the projectile is launched. At low speeds the projectile travels in a near parabolic trajectory before collision with the earth's surface. At a speed of about 8000 metres per second the projectile will maintain a circular path just above the earth. At greater speeds the path becomes elliptical until at about 11,000 metres per second the shape of the trajectory becomes parabolic and the projectile never returns to the earth.

Newton's laws were developed as an explanation for the movement of planets, not as an aid for man in his attempt to reach the moon. Only after the development of recent technology did the theories of Newton become applicable to orbiting spacecraft. Apollo 8 astronauts gave recognition to Newton's contribution to the space program when in returning from the moon, they replied to ground control's question, "Who's driving up there?" with the statement "I think Isaac Newton is doing most of the driving right now".

Newton's System of the World



"...the greater the velocity...with which (a stone) is projected, the farther it goes before it falls to the earth. We may therefore suppose the velocity to be so increased, that it would describe an arc of 1, 2, 5, 10, 100, 1000 miles before it arrived at the earth, till at last, exceeding the limits of the earth, it should pass into space without touching it."

*Q11 Summarize the dividends from the law of gravity discussed in this section.

*Q12 What do you think the astronaut meant when he said, "I think Isaac Newton is doing most of the driving right now"?

9.6 The Discovery of Neptune

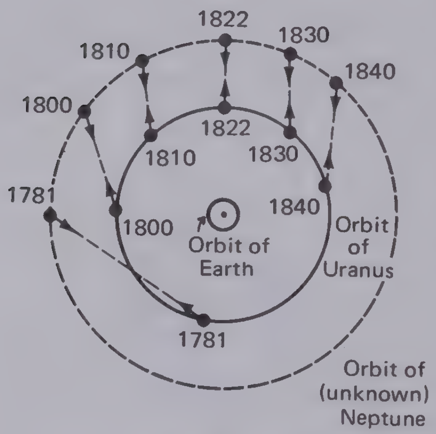
Mercury, Venus, Earth, Mars, Jupiter, and Saturn remained the only observed planets of the solar system until 1781 when William Herschel made a most exciting telescopic observation. He saw a very bright, starlike object which appeared to move relative to the stars. Further observations proved this to be a planet which was later named Uranus. Observations of the orbit of this planet showed that it did not exactly obey Kepler's laws of planetary motion.

William Herschel: British astronomer and telescope maker, 1738-1822.

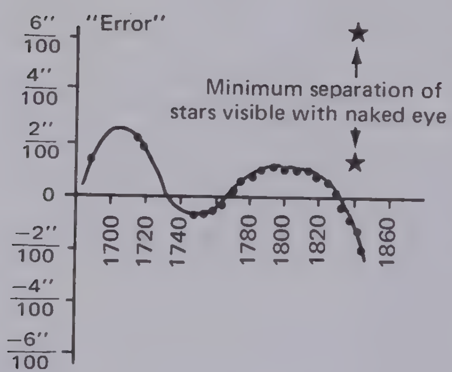
This was not unusual. Newton realized that although the main influence on a planet's motion is the sun, each of the major objects in the solar system has a small effect on each of the others. The extent of this force depends upon their masses and their distance from each other. Such minor variations in the orbits are called *perturbations* and can be explained by Newton's Law of Gravitation. However, a detailed analysis of the motion of Uranus showed that even after correcting for the forces of the other planets on Uranus there still remained an unexplained perturbation of some hundredths of a degree. Could Newton's law of gravity be in error?

The word perturbation is derived from the Latin verb, *turbare,* to disturb.

The story of this discovery is told in *The Discovery of Neptune* by Morton Grosser, Harvard Press.



Perturbing Forces on Uranus, Due to Neptune.



Residual "Unexplained" Perturbations of Uranus (A.D. 1650-1850).

The constant testing of predictions based on accepted scientific laws is a most important step in the method of science. Newton's law of gravity predicted a certain orbit for Uranus. The planet did not follow this orbit exactly. Perhaps the law on which this prediction was made was not correct. The "truths" of science must be kept under continuous examination.

Two mathematicians did not believe that Newton's law was in error and assumed that the unexplained perturbation was caused by another planet as yet unseen. Independently, the English mathematician, John Adams, and the French astronomer, Urbain Leverrier through perseverance and mathematical ability predicted the orbit, mass, and position of a planet thereby accounting for the observed and unexplained perturbation. They each wrote to observatories with this information.

> "According to my calculations, the observed irregularities in the motion of Uranus may be accounted for by supposing the existence of an exterior planet, the mass and orbit of which are as follows. . ."
>
> Adams to Airy, October 21, 1845.

> "It is impossible to satisfy the observations of Uranus without introducing the action of a new planet, thus far unknown. . . . Here are the elements of the orbit which I assign to this body. . ."
>
> Leverrier to Galle, September 18, 1846.

Although Adams wrote his letter almost a year before Leverrier he did not receive a reply. The astronomers to whom he wrote did not believe that a planet's position could be predicted with only a pen, paper, and perseverance. The reply came to Leverrier:

> "The planet whose position you have pointed out actually exists. . ."
>
> Galle to Leverrier, September 25, 1846.

The prediction of the position of an unseen body as a result of its effect on a planet was an excellent test of the validity of the Law of Gravitation.

Q13 Some writers have said that the planet Neptune was really discovered by Isaac Newton. What do they mean?

***Q14** Are planetary orbits really ellipses with the sun at one focus as stated by Kepler?

See problem 9.10 on page 78.

9.7 What is Gravity?

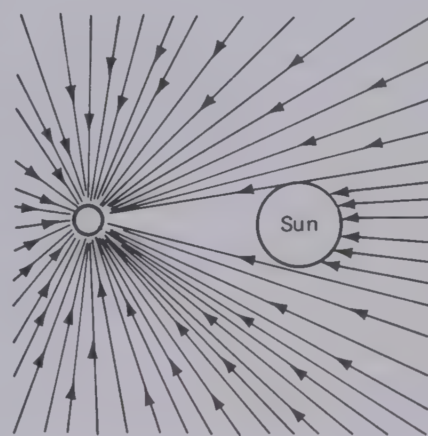
Many people, when they ask the question, What is gravity? want to hear an explanation involving a mechanism which would operate between objects and pull them toward each other in the manner of an elastic band or spring. Such a mechanism would have to account for the variety of unusual properties of this force. Gravity is a property of all matter. It extends across very large distances, even in a vacuum, and it cannot be shielded by any substance.

Many mechanisms were proposed by others but none were successful. They either did not satisfy the planetary observations

or suggested other phenomena which had not been detected. One proposed mechanism suggested that all objects in space were being continuously bombarded by a rain of particles. In most cases since this rain would fall equally from all directions there would be no net force on the object. However, consider a planet in the solar system. Particles coming from space toward the planet from the direction of the sun would be stopped by the sun. This would mean that there would be a net force acting on the planet toward the sun. Hence, a possible explanation for gravity. However, we must dismiss this suggestion because it introduces a major contradiction. If a planet as it circled the sun, were being continuously bombarded by particles from space, more particles would hit it from the front than the back. This would result in a net force opposing the planet's circular motion which would in a short time cause the planet to slow down and eventually spiral into the sun. The earth has been in its orbit much too long to substantiate this theory.

A man running in the rain appears to receive more raindrops from the direction toward which he is running.

But would gravity be better explained if it were shown to be the result of some mechanism? Let us suppose that it could be shown that the force acting on the planets was the result of vortices in the aether, as suggested by Descartes. (This suggestion would certainly lack the elegance of Newton's law.) Would we not then ask for a mechanism to explain the forces that act between the particles which make up the vortices? The adoption of one mechanism often introduces the need for others. A mechanism is not necessarily a final solution to a problem and the search for a final solution may often be regarded as futile.



Sun blocks many particles coming from the right.

It was suggested by some of Newton's contemporaries that his law was merely a useful mathematical model and did not explain what really was happening. This is similar to an earlier criticism of Ptolemy's model of the solar system. Ptolemy was thought by many to have made a description that was useful for mathematical predictions but did not really describe the way things were. Newton, however, regarded his law as an exact description of the force of gravity. That this description was expressed in mathematical terms was a matter of convenience and did not indicate that it was merely useful for calculations.

Another property of gravity that puzzled scientists was that it acted continuously. Newton regarded the constant action of this force as an example of a "continuous miracle". He believed that the action of gravity was evidence of the constant attention of a creator to the universe. Although he may have sought a mechanism for this miracle, he offered no suggestion publicly. When asked for a cause of gravity, he answered "I propose no hypothesis". This did not mean that Newton never used hypotheses in his work. He, like any other scientist, was constantly making suggestions and guesses which he thought might be correct. It is part of the method of science to do so. However, in the case of gravity he refused to make suggestions for a gravitational mechanism which he felt was not testable during his lifetime.

The original Latin in the *Principia* said "hypotheses non fingo".

It is important to distinguish between what Newton explained and what he did not explain. Although Newton did not

offer an explanation for the mechanism by which gravity acts, he did offer a simple mathematical expression of this force which satisfied many observed and seemingly unrelated phenomena. The major ideas of science are both simple in expression and extensive in application. A falling apple, planetary motions, tides, comets, and perturbations were all linked by this simple law of gravity. Newton's achievement was to see a unity and a connection which had not been seen before. The unity was that of the objects on the earth and those in the heavens. The connection was between the motion of a falling apple and the moon.

*Q15 What is meant when we say that Newton's Law of Gravitation offers no mechanism to explain gravity?

See problems 9.11 to 9.13 on page 78.

9.8 The Cultural Impact of the Newtonian Viewpoint

In this unit we started at the beginnings of recorded history and followed the attempts of men to explain the cyclic motions observed in the heavens. We had several purposes. The first was to examine with some care the difficulties of changing from an earth-centered view of the heavens to the modern one in which the earth came to be seen as just another planet moving around the sun. We also wanted to put into perspective Newton's synthesis of earthly and heavenly motions. From time to time we have also suggested that there was an interaction of these new world views with the general culture. We stressed that each contributor was a creature of his times, limited in the degree to which he could abandon the teachings on which he was reared. Gradually, through the successive work of many, a new way of looking at heavenly motions arose. This in turn opened new possibilities for even further new ideas, and the end is not in sight.

Still another purpose was to see how theories are made and tested, what is the place of assumption and experiment, of mechanical models and mathematical description. In later parts of the course, we shall come back to the same questions in more recent context, and we shall find that the attitudes developed towards theory-making during the seventeenth-century scientific revolution are still immensely fruitful today.

In our study we have referred to scientists in Greece, Egypt, Poland, Denmark, Austria, Italy, England, and other countries. Each, as Newton said, stood on the shoulders of others. And for each major success there were many lesser advances or, indeed, failures. We have seen science as a cumulative intellectual activity not restricted by national boundaries or by time. It is not inevitably and relentlessly successful, but it grows more as a forest grows, new growth replacing and drawing nourishment from the old, sometimes with unexpected changes in its different parts. It is not a cold, calculated pursuit, for it may involve

passionate controversy, religious convictions, esthetic judgments of what beauty is, and sometimes private, wild speculation.

It is also clear that the Newtonian synthesis did not put an end to the study of science by solving all problems. In many ways it opened whole new lines of investigations, both theoretical and observational. In fact, much of our present science and also our technology had its effective beginnings with the work of Newton. New models, new mathematical tools, and new self-confidence (sometimes misplaced, as the study of the nature of light will show) encouraged those who followed, to attack the new problems. A never-ending series of questions, answers, and more questions was well launched. The modern view of science is that it is a continuing quest into ever more interesting fields.

Among the many problems remaining after Newton's work was the study of objects interacting not by gravitational forces, but by friction and collision. This led, as the next unit shows, to the concepts of *momentum* and *energy*, and then to a much broader view of the connection between different parts of science—physics, chemistry, and biology. Eventually, from this line of study, emerged other statements as grand as Newton's law of universal gravitation: the conservation laws on which so much of modern science and technology is based, especially the part having to do with many interacting bodies making up a system. That account will be the main subject of Unit 3.

Newton's influence was not, however limited to science alone. The century following the death of Newton in 1727 was a period of consolidation and further application of Newton's discoveries and methods, whose effects were felt especially in philosophy and literature, but also in many other fields outside science. Let us round our view of Newton by considering some of these effects.

During the 1700's, the so-called Age of Reason or Century of Enlightenment, the viewpoint called the Newtonian cosmology became firmly entrenched in European science and philosophy. The impact of Newton's achievements may be summarized thus: he had shown that man, by observing and reasoning, by considering mechanical models and deducing mathematical laws, could uncover the workings of the physical universe. Therefore, it was argued, man should attempt by the same method to understand not only nature but also society and the human mind. As the French writer Fontenelle (1657-1757) expressed it:

> The geometric spirit is not so bound up with geometry that it cannot be disentangled and carried into other fields. A work of morals, or politics, of criticism, perhaps even of eloquence, will be the finer, other things being equal, if it is written by the hand of a geometer.

The English philosopher John Locke (1632-1704) was greatly influenced by Newton's work and in turn reinforced Newton's influence on others; he argued that the goal of philosophy should be to solve problems, including those that affect our daily life, by observation and reasoning. "Reason must be our best judge and guide in all things," he said. Locke thought that the concept of "natural law" could be used in religion as well as

in physics; and indeed the notion of a religion "based on reason" appealed to many Europeans who hoped to avoid a revival of the bitter religious wars of the 1600's.

Locke advanced the theory that the mind of the new-born child contains no "innate ideas"; it is like a blank piece of paper on which anything may be written. If this were true, it would be futile to search within oneself for a God-given sense of what is true or morally right. Instead, one must look at nature and society to discover whether there are any "natural laws" that may exist. Conversely, if one wants to improve the quality of man's mind, one must improve the society in which he lives.

Locke's view also implied an "atomistic" structure of society: each person is separate from other individuals in the sense that he has no "organic" relation to them. Previously, political theories had been based on the idea of society as an organism in which each person has a prescribed place, function, and obligation. Later theories, based on Locke's ideas, asserted that government should have no fuction except to protect the freedom and property of the individual person.

Although "reason" was the catchword of the eighteenth-century philosophers, we do not have to accept their own judgment that their theories about improving religion and society were necessarily the most reasonable. Like most others, these men would not give up a doctrine such as the equal rights of all men merely because they could not find a strictly mathematical or scientific proof for it. Newtonian physics, religious toleration, and republican government were all advanced by the same movement; but this does not mean there was really a logical connection among them. Nor, for that matter, did many of the eighteenth-century thinkers in any field or nation seem much bothered by another gap in logic and feeling; they believed that "all men are created equal," and yet they did little to remove the chains of black slaves, the ghetto walls imprisoning Jews, or the laws that denied voting rights to women.

Still, compared with the previous century, the dominant theme of the 1700's was *moderation*—the happy medium, based on toleration of different opinions, restraint of excess in any direction, and balance of opposing forces. Even reason was not allowed to ride roughshod over religious faith; atheism, which some philosophers thought to be the logical consequence of unlimited rationality, was still regarded with horror by most Europeans.

The Constitution of the United States of America, with its ingenious system of "checks and balances" to prevent any faction from getting too much power, is one of the most enduring achievements of this period. It attempts to establish in politics a stable equilibrium of opposing trends similar to the balance between the sun's gravitational pull and the tendency of a planet to fly off in a straight line. If the gravitational attraction increased without a corresponding increase in planetary speed, the planet would fall into the sun; if its speed increased without a corresponding increase in gravitational attraction, the planet would escape from the solar system.

Just as the Newtonian laws of motion kept the earth at its proper distance from the sun, so the political philosophers, some of whom used Newtonian physics as a model of thought, hoped to devise a system of government which would avoid the extremes of dictatorship and anarchy. According to James Wilson (1742-1798), who played a major role in drafting the American Constitution:

> In government, the perfection of the whole depends on the balance of the parts, and the balance of the parts consists in the independent exercise of their separate powers, and, when their powers are separately exercised, then in their mutual influence and operation on one another. Each part acts and is acted upon, supports and is supported, regulates and is regulated by the rest. It might be supposed, that these powers, thus mutually checked and controlled, would remain in a state of inaction. But there is a necessity for movement in human affairs; and these powers are forced to move, though still to move in concert. They move, indeed, in a line of direction somewhat different from that, which each acting by itself would have taken; but, at the same time, in a line partaking of the natural directions of the whole—the true line of public liberty and happiness.

A related effect of Newton's work in physics on other fields was the impetus Newton as a person and Newton's writing gave to the idea of political democracy. A former farm boy had penetrated to the outermost reaches of the human imagination, and what he found there meant, first of all, that God had made only one set of laws for heaven and earth. This smashed the old hierarchy and raised what was once thought base to the level of the noble. It was an extension of a new equality throughout the universe: Newton had shown that all matter, whether of sun or of ordinary stone, was created equal, was of the same order in "the Laws of Nature and of Nature's God," to cite the phrase used at the beginning of the Declaration of Independence to justify the elevation of the colonists to an independent people. The whole political ideology was heavily influenced by Newtonian ideas. The *Principia*, many thought, gave an analogy and extension direct support to the proposition being formulated also from other sides, that all men, like all natural objects, are created equal before nature's creator.

In literature, too, many welcomed the new scientific viewpoint as a source of metaphors, allusions, and concepts which they used in their poems and essays. Newton's discovery that white light is composed of colours was referred to in many poems of the 1700's (see Unit 4). Samuel Johnson advocated that words drawn from the natural sciences be used in literary works, defining such words in his *Dictionary* and illustrating their application in his "Rambler" essays.

Other writers distrusted the new cosmology and so used it for purposes of satire. In his epic poem *The Rape of the Lock*, Alexander Pope exaggerated the new scientific vocabulary for comic effect. Jonathan Swift, sending Gulliver on his travels to Laputa, described an academy of scientists and mathematicians whose experiments and theories were as absurd as those of the Fellows of the Royal Society must have seemed to the layman of the 1700's.

The first really powerful reaction against Newtonian cosmology was the Romantic movement, begun in Germany about 1780 by young writers inspired by Johann Wolfgang von Goëthe. The most familiar examples of Romanticism in English literature are the poems and novels of Blake, Coleridge, Wordsworth, Shelley, Byron, and Scott.

The Romantics scorned the mathematical view of nature, and emphasized the importance of quality rather than quantity. They preferred to study the unique element of an individual person or experience, rather than make abstractions. They exalted emotion and feeling at the expense of reason and calculation. In particular, they abhorred the theory that the universe is in any way like a clockwork, made of inert matter set into motion by a God who never afterwards shows His presence. Reflecting this attitude, the historian and philosopher of science, E. A. Burtt, has written scathingly that:

> . . . the great Newton's authority was squarely behind that view of the cosmos which saw in man a puny, irrelevant spectator (so far as being wholly imprisoned in a dark room can be called such) of the vast mathematical system whose regular motions according to mechanical principles constituted the world of nature. The gloriously romantic universe of Dante and Milton, that set no bounds to the imagination of man as it played over space and time, had now been swept away. Space was identified with the realm of geometry, time with the continuity of number. The world that people had thought themselves living in—a world rich with colour and sound, redolent with fragrance, filled with gladness, love and beauty, speaking everywhere of purposive harmony and creative ideals—was crowded now into minute corners in the brains of scattered organic beings. The really important world outside was a world hard, cold, colourless, silent, and dead; a world of quantity, a world of mathematically computable motions in mechanical regularity. The world of qualities as immediately perceived by man became just a curious and quite minor effect of that infinite machine beyond.

Because in their view, the whole (whether it be a single human being or the entire universe) is pervaded by a spirit that cannot be rationally explained but can only be intuitively felt, the Romantics insisted that phenomena cannot meaningfully be analyzed and reduced to their separate parts by mechanistic explanations.

Continental leaders of the Romantic movement, such as the German philosopher Friedrich Schelling (1775-1854) proposed a new way of doing scientific research, a new type of science called "Nature Philosophy." (This term is not to be confused with the older "natural philosophy," meaning mainly, physics.) The Nature Philosopher does not analyze phenomena such as a beam of white light into separate parts or factors which he can measure quantitatively in his laboratory—or at least that is not his primary purpose. Instead, he tries to understand the phenomenon as a whole, and looks for underlying basic principles that govern all phenomena. The Romantic philosophers in Germany regarded Goëthe as their greatest scientist as well as their greatest poet, and they pointed in particular to his theory of colour, which flatly contradicted Newton's theory of light. Goëthe held that white light does not consist of a mixture of colours but rather that the colours are produced by the prism acting on and changing the light which was itself pure.

In the judgment of all modern physicists, Newton was right and Goëthe wrong. Yet, in retrospect, Nature Philosophy was not simply an aberration. The general tendency of Nature Philosophy did encourage speculation about ideas which could never be tested by experiment; hence, Nature Philosophy was condemned by most scientists. But it is now generally agreed by historians of science that Nature Philosophy played an important role in the historical origins of some scientific discoveries. Among these was the general principle of conservation of energy, which is described in Chapter 11. The recognition of the principle of conservation of energy came in part out of the viewpoint of Nature Philosophy, for it asserted that all the "forces of nature"—the phenomena of heat, gravity, electricity, magnetism, and so forth—are manifestations of one underlying "force" (which we now call energy).

Much of the dislike which Romantics expressed for science was based on the mistaken notion that scientists claimed to be able to find a mechanistic explanation for *everything*, including the human mind. If everything could be explained by Newtonian science, then everything would also be *determined* in the way the motions of different parts of a machine are determined by its construction. Most modern scientists no longer believe this, but some scientists in the past have made statements of this kind. For example, the French mathematical physicist Laplace (1749-1827) said:

> We ought then to regard the present state of the universe as the effect of its previous state and as the cause of the one which is to follow. Given for one instant a mind which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it—a mind sufficiently vast to submit these data to analysis—it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.

Even the ancient Roman philosopher Lucretius (100-55 B.C.), who supported the atomic theory in his poem *On the Nature of Things*, did not go as far as this. In order to preserve some vestige of "free will" in the universe, Lucretius suggested that the atoms might swerve randomly in their paths. This was still unsatisfactory to the Romantics and also to some scientists such as Erasmus Darwin (grandfather of evolutionist Charles Darwin), who asked:

> Dull atheist, could a giddy dance
> Of atoms lawless hurl'd
> Construct so wonderful, so wise,
> So harmonised a world?

The Nature Philosophers thought they could discredit the Newtonian scientists by forcing them to answer this question; to say "yes," they argued, would be absurd, and to say "no" would be disloyal to their own supposed beliefs. We shall see how successful the Newtonians were in explaining the physical world without committing themselves to any definite answer to Erasmus Darwin's question. Instead,they were led to the discovery of immensely powerful and fruitful laws of nature, discussed in the next units.

Problems Chapter 9

Use $G = 6.7 \times 10^{-11} \frac{\text{N-m}^2}{\text{kg}^2}$

Section A

9.1 How did Newton verify the inverse square nature of gravitational force?

9.2 Sketch a graph showing the gravitational force between two objects as a function of their separation.

9.3 What effect would the following changes of separation between two objects have on the gravitational force between them?

Distance is

a) increased by 10.
b) increased by 3.
c) decreased to one-tenth.
d) decreased to one-third.

*9.4 It has been claimed that the dependence of the gravitational force on the masses of both interacting bodies could be expressed as $m_{sun}\ m_{planet}$. To test alternatives to using the product, consider the possibilities that the force could depend upon the masses in either of two ways:

a) total force depends on $(m_{sun} + m_{planet})$
or
b) total force depends on (m_{sun}/m_{planet}).

What would these relationships imply would happen to the force if either mass were reduced to zero? Would there still be a force even though there were only one mass left? Could you speak of a gravitational force if there were no body to be accelerated?

9.5 The sun's mass is about 27,000,000 times greater than the moon's mass; the sun is about 400 times farther from the earth than the moon is. How does the gravitational force exerted on the earth by the sun compare with that exerted by the moon?

*9.6 Use the values for the mass and size of the moon (see table on page 85) to show that the "surface gravity" (acceleration due to gravity near the moon's surface) is only about one-sixth of what it is near the earth.

*9.7 Using the information given in the chart on page 85 and the formula $F = G\frac{m_1\,m_2}{R^2}$ show that the acceleration due to gravity at the earth's surface is 9.8 m/s^2.

9.8 The determination of a value of G made it possible to calculate the mass of the earth, and therefore its average density. The "density" of water is 1000 kg per cubic metre. (That is, for any sample of water, dividing the mass of the sample by its volume gives 1000 kg/m^3.)

a) What is the earth's average density?
b) The densest kind of rock known has a density of about 5000 kg/m^3. Most rock we find has a density of about 3000 kg/m^3. What do you conclude from this about the structure of the earth?

*9.9 Calculate the mass of the earth from the fact that a 1 kg object at the earth's surface is attracted to the earth with a force of 9.8 newtons. The distance from the earth's centre to its surface is 6.4×10^6, metres. Check this value with the one given in the chart on page 85. How many times greater is this than the greatest masses which you have had some experience in accelerating (for example, cars)?

*9.10 The article on page 80 describes the possible discovery of a planet beyond Pluto.
(a) What is the method used in its discovery?
(b) Could you suggest another explanation without suggesting the existence of a planet?
(c) What steps would have to be taken to show that this proposed planet really exists?

*9.11 Why was Newton's theory of gravitation called a universal law?

*9.12 What happened to Plato's problem? Was it solved?

*9.13 The making of theories to account for observations is a major purpose of scientific study. Therefore, some reflection upon the theories encountered thus far in this course will be useful. Comment in a paragraph or more, with examples from Units 1 and 2, on some of the statements below. Look at all the statements and select at least four, in any order you wish.

a) A good theory should summarize and not conflict with a body of tested observations. (For example, Kepler's unwillingness to explain away the difference of eight minutes of arc between his predictions and Tycho's observations.)
b) There is nothing more practical than a good theory.
c) A good theory should permit predictions of new observations which sooner or later can be made.
d) A good new theory should give almost the same predictions as older theories for the range of phenomena where they worked well.
e) Every theory involves assumptions. Some involve also esthetic preferences of the scientist.
f) A new theory relates some previously unrelated observations.
g) Theories often involve abstract concepts derived from observation.
h) Empirical laws or "rules" organize many observations and reveal how changes in one quantity vary with changes in another, but such laws provide no explanation of the causes or mechanisms.
i) A theory never fits all data exactly.
j) Predictions from theories may lead to the observation of new effects.
k) Theories that later had to be discarded may have been useful because they encouraged new observations.

l) Theories that permit quantitative predictions are preferred to qualitative theories.
m) An "unwritten text" lies behind the statement of every law of nature.
n) Communication between scientists is an essential part of the way science grows.
o) Some theories initially seem so strange that they are rejected completely or accepted only very slowly.
p) Models are often used in the making of a theory or in describing a theory to people.
q) The power of theories comes from their generality.

Section B

*9.14 Accepting the validity of $F_{grav} = Gm_1m_2/R^2$, and recognizing that G is a universal constant, we are able to derive, and therefore to understand better, many particulars that previously seemed separate. For example, we can conclude:
a) That a_g for a body of any mass m_o should be constant at a particular place on earth.
b) That a_g might be different at places on earth at different distances from the earth's centre.
c) That at the earth's surface the weight of a body is related to its mass.
d) That the ratio R^3/T^2 is a constant for all the satellites of a body.
e) That high tides occur about twelve hours apart.
Describe briefly how each of these conclusions can be derived from the equation.

*9.15 The mass of the earth can be calculated also from the distance and period of the moon. Show that the value obtained in this way agrees with the value calculated from measurements at the earth's surface. (See table on page 85.)

9.16 Newton was able to determine the masses of planets having moons, in terms of the mass of the sun, by using his Law of Gravitation and information of periods of the moon. The general equation for circular orbits,

$$F = G\frac{m_1 m_2}{R^2} = \frac{4\pi^2 mR}{T^2},$$

may be written for a planet p orbiting the sun s as

a) $$G\frac{m_p\, m_s}{R^2{}_p} = \frac{4\pi^2 m_p R_p}{T^2{}_p},$$

and for the moon orbiting the planet as,

b) $$G\frac{m_p m_m}{R^2{}_m} = \frac{4\pi^2 m_m R_m}{T^2{}_m}.$$

Dividing b) by a)

$$\frac{R^2{}_p}{R^2{}_m} \times \frac{m_m}{m_s} = \frac{m_m R_m}{T^2{}_m} \times \frac{T^2{}_p}{m_p R_p}$$

$$\frac{m_p}{m_s} = \frac{R^3{}_m}{R^3{}_p} \times \frac{T^2{}_p}{T^2{}_m}.$$

Use this equation to determine the mass of Jupiter in terms of the mass of the sun, given that Jupiter's moon, Callisto, has a period of 16.7 days and an orbital radius of 1/80 AU.

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THE EFFECT OF A TRANS-PLUTONIAN PLANET ON HALLEY'S COMET

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An orbit and mass for a hypothetical trans-Plutonian planet is determined which reduces the residuals in the time of perihelion passage of Halley's comet at the seven apparitions from 1910 to 1456 by 93%. The effect of this hypothetical planet on the major planets is briefly discussed, and it is shown that the residuals of two similar periodic comets, Olbers and Pons-Brooks, are also improved.

Key words: comet—Halley's comet—planet—trans-Plutonian

I. Introduction

There is no logical reason to suppose Pluto to be the outermost planet of the solar system. Indeed, there is a great deal of evidence indicating that it is not, and the literature of the last 100 years records numerous attempts to predict planets beyond Neptune and Pluto, some of which have led to telescopic searches. Among the early predictions were Forbes (1880), Todd (1880), and Gaillot (1909); and more recently, Sevin (1946, 1949), Strubell (1953), and Kritzinger (1958, 1963). But the most famous were Pickering's (1909, 1928) with its discouraging conclusion and, of course, the fruitful prediction of Percival Lowell (1915). Throughout this literature, the most consistent message is that there must be two trans-Neptunian planets. One of these is now Pluto and the other one appears to be about twice the distance of Neptune from the sun.

Whether Pluto was actually Lowell's planet X, or its discovery an extraordinary coincidence as Brown (1930, 1931) claimed, or fortuitous as Kourganoff (1941) indicates in his refutation of Brown, is still an intriguing question. But even more intriguing is the consistent failure of the theories of Neptune's motion to represent the observations. As indicated by Rawlins (1970), the unexplained residual in the orbit of Neptune may be due to an alien perturbation; but years may have to pass before planetary residuals will reveal the position of a trans-Plutonian planet.

However, Halley's comet, which has been observed for over 2000 years, might provide the necessary record from which the orbit of a planet beyond Pluto can be found. Obviously this is not a continuous record. Most are perihelion passages at approximately 76-year intervals and all but the last four are pretelescopic. Nevertheless, there are two millennia of recorded observations. Furthermore, the effectiveness of a disturbing body is a direct function of the eccentricity of the disturbed body, and P/Halley, with its large eccentricity, would be more highly disturbed by a trans-Plutonian mass than the major planets.

In order to link several apparitions of Halley's comet, Brady and Carpenter (1971) found it necessary to include a secular term in the equations of motion. This secular term needs no apology. Its purpose was to provide a good prediction for the 1986 return—but it does much more. It represents the motion of the comet for a very long period of time, possibly for more than 2000 years, and in many cases better than indicated by the presently accepted catalog values. But even if the secular term needs no defense it would be more meaningful if it had a physical intepretation. To attribute it to nongravitational forces is one possibility and due mainly to the work of Marsden (1968), it is now generally accepted that there are such forces affecting many short-period comets. With comets of longer periods, however, another possible explanation is an alien perturbation, suggesting that the force is gravitational after all.

What follows is a report on a numerical experiment to determine if it is possible to represent the motion of Halley's comet over a long period of time by including the effect of a hypothetical planet beyond Pluto. The solution is a numerical-graphical one, and this brief summary greatly oversimplifies the process, failing completely to give a true picture of the actual amount of computing.

The first step determined an approximation for the semimajor axis and mass of the hypothetical planet from the residuals of Halley's comet. With this semimajor axis and mass, and with the eccentricity and inclination equal to zero, the second step determined a starting longitude. With this semimajor axis, mass, and starting longitude, and with the eccentricity still zero, the third step determined the inclination and the longitude of the node. With these five elements known, the last step determined the eccentricity and the argument of perihelion.

The integrations were all done on a CDC 6600 computer with an n-body code (McMahon 1970), using the planetary starting values of Lieske (1967) with the masses of the planets modified according to Clemence (1965).

Epilogue

A Modern View of the Universe

Since the time of Newton there have been many developments in the technology of optical instruments and electronics which have led to a profound increase in man's knowledge of astronomy. Because of these developments, man's modern view of the universe is very different from that of the seventeenth century astronomers. However, the concept of gravity introduced by Isaac Newton still plays a major role in our twentieth century description. The sun is no longer considered a unique object but is simply one of the stars which make up the galaxy called the Milky Way. The Milky Way contains about a hundred billion stars and has a diameter of 80,000 light years. When we look into the night sky along the plane of the galaxy, we see the many stars that lie in its wide band. Our sun is located about 30,000 light years from the centre of the galaxy in one of the spiral arms, where it travels in an elliptical orbit about the centre, once in every 230 million years. The orbit of the sun in the galaxy may be calculated using Newton's laws of motion in the same manner in which they were used to calculate the orbit of the planets.

Looking beyond the Milky Way we see that it is just one of the seemingly countless galaxies that make up the universe. These galaxies have been observed to the limits of our present telescopes. Some of the early observations of distant galaxies were carried out by Edwin Hubble in the mid-1920's at the Mount Wilson Observatory in California. He was able to determine estimates for both the distances and the velocities at which these objects were moving. His calculations showed a very interesting pattern. All the distant galaxies seemed to be moving away from the Milky Way at a velocity which was proportional to their distance from its centre. It appeared almost as if we were at the centre of the universe and the other galaxies were moving away from us. This would suggest a possible explosive creation of the universe.

Let us use an analogy to illustrate Hubble's observation. In Fig. 1 we see the start of an auto race in which one group of cars is lined up to proceed west and the other east along a straight highway. Fig. 2 shows the view of this car race four hours after the start. The chart shows both the velocity with which the cars have been proceeding and the distance from the starting line they have travelled in four hours. Let us now describe the view of a person standing at the starting line as he looks east and west at the cars four hours after the start of the race. He would observe that all the cars seem to be travelling away from him at velocities that are proportional to their distance.

CAR	Speed Km/hr.	Distance Km
	MEASURED FROM start	
A	85	340
B	70	280
C	60	240
D	50	200
E	20	80
F	0	0
G	10	40
H	30	120
I	40	160
J	60	240

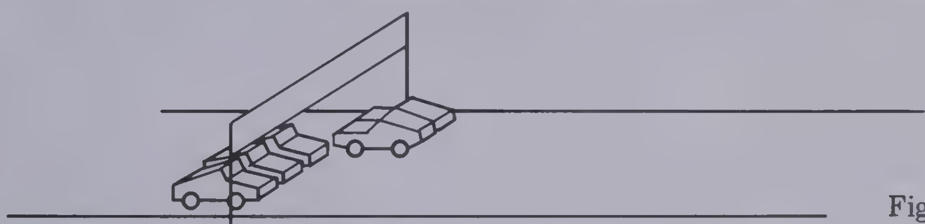


Fig. 1

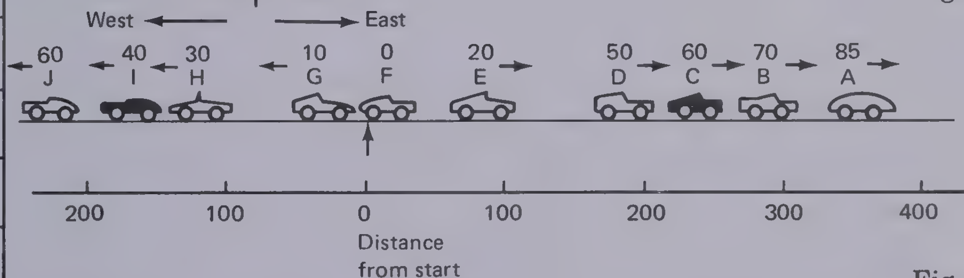


Fig. 2

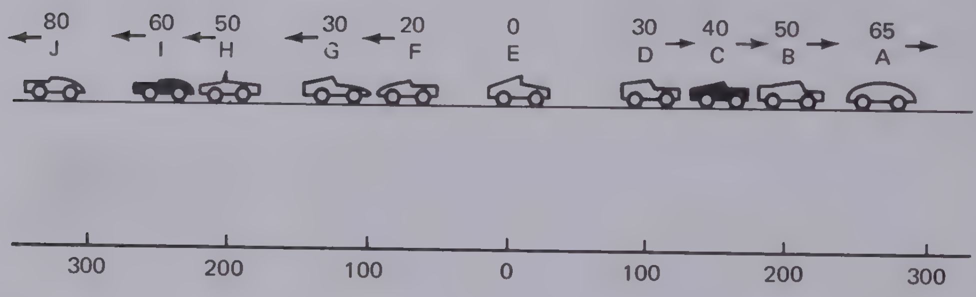
Within our galaxy we observe many objects whose motion or appearance is explained by Newton's Law of Gravitation. We see pairs of stars, called binaries, located close enough together that their mutual forces of gravity cause them to rotate about each other. Large collections of stars called globular clusters which are held together by gravitional force have been photographed, and large clouds of gas which seem to be collapsing under the force of gravity causing the formation of new stars at their centres, have been observed.

From the values of the distances and velocities of these cars, he can easily calculate how long ago the race began. For example, knowing that car *C* is travelling away from him at a velocity of sixty kilometres per hour and that it is at a distance of 240 kilometres from him, he can use the information in Unit 1 of this course to calculate a starting time of $\frac{240 \text{ km}}{60 \text{ km/hr}} =$ 4 hours ago. Does this mean that the Milky Way galaxy is at the centre of the universe? Can we use Hubble's observations to calculate the "starting time"

of the universe?

To answer these questions let us consider the view of the race as seen from a passenger in car E. This view has been sketched in Fig. 3.

The chart shows the distance of the cars from car E and their velocity measured relative to car E. The passenger in car E would make the following observation: All the other cars are moving away from him with velocities which are proportional to their distance. In fact, it doesn't matter from which car we choose to make our observations. They would all make the same general observation concerning the motion of the other cars in the race and the manner in which their observed velocity depends upon their distance. Thus, although it may appear to an observer in car E that he is at the centre of the race, his conclusion is not correct. However, knowing the apparent velocity and distance of another car in the race, it is possible for him to calculate when the race started. If you take the data in the chart for any car, as seen from car E, you can show that car E and the other car were together four hours ago.



CAR	Speed Km/hr.	Distance Km
	Measured from Car E	
A	65	260
B	50	200
C	40	160
D	30	120
E	0	0
F	20	80
G	30	120
H	50	200
I	60	240
J	80	320

Fig. 3

By using reasoning similar to that of our analogy, Edwin Hubble concluded that the universe was in a state of expansion possibly caused by a giant explosion. Hubble estimated that the time of this explosion was about ten billion years ago. In his expanding universe, gravity plays a most important role. As the galaxies travel through space at high speeds, the force of gravity acts on them, slowing them down as it tends to pull them back to the centre. One question in current astronomy is, "Will the force of gravity be great enough to eventually stop this outward motion of galaxies and cause them to return? " If it should be, then perhaps the history of the universe may be one of a series of cosmic explosions. If it should not be, then perhaps the galaxies are heading towards an eternity of isolation.

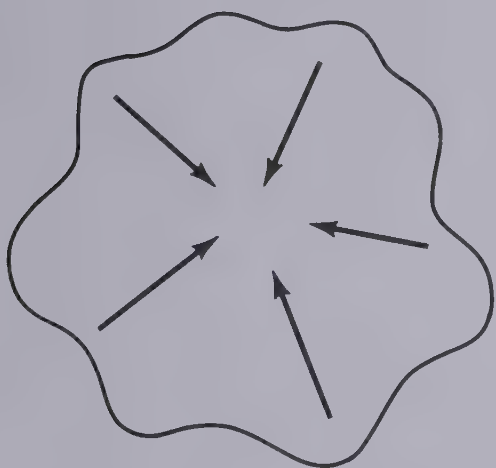
Many of the questions we ask about the universe have not changed very much in the past two thousand years. We still wonder about its size, its origin, and the significance of man in it. However, the framework in which these questions are asked has changed and is in fact still changing. As we look back on the view of the Greeks and compare it with our own, it is tempting to look forward into the future and anticipate the manner in which our twentieth century views will be received by future generations of scientists.

One question that modern astronomers have attempted to answer concerns the evolution of a star. The Greeks considered the apparent unchanging nature of the stars to be an indication of their perfection. However, modern astronomers describe stars as an evolving form of matter having a "lifetime" of many billions of years. The concept of gravitational force is most important in a twentieth century astronomer's description of the life of a star.

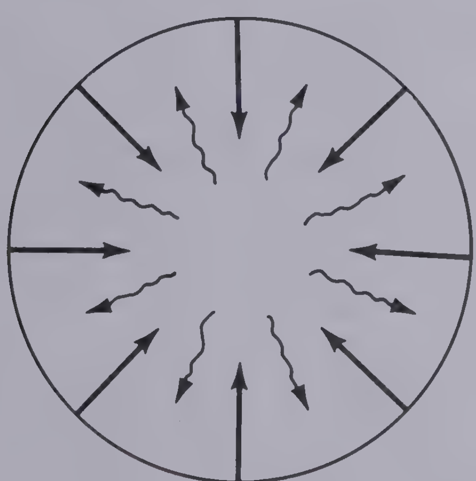
A star begins its life as a gaseous cloud of matter made up of hydrogen gas and small amounts of other elements, and many hundreds of millions of kilometres in diameter. Gravitational force causes this cloud to condense toward its centre, gradually forming a denser core which will attract even more matter. As the matter falls toward the central core it produces some heat which passes through the cloud into the surrounding space. As time passes and more matter is pulled by gravity into this core it becomes so dense that it begins to trap the heat energy in its centre. Scientists refer to the gas cloud as becoming "opaque to its heat radiation" at this stage. The build-up of heat at the centre of the core, as a result of the initial gravitational collapse of the dust cloud, is a most important step in stellar evolution. As a result of this rise in internal temperature the pressure at the core of the cloud increases, much as in a pressure cooker.

The 'star' has then reached a state of delicate balance between the gravitational force pulling the star together and the pressure in the interior trying to blow it apart. Some small clouds formed in this manner never obtain a high enough central temperature to

produce sufficient pressure to balance the force of gravity. These objects collapse into a very dull dense star called a Black Dwarf star. On the other hand, some stars contain too much mass and hence produce a central pressure that overcomes the force of gravity causing the cloud to become unstable and either shed some of its mass or break up into smaller clouds which may eventually form their own stars. However, if the mass is between one-tenth of one solar mass and eighty solar masses, a balance between gravity and radiation pressure is achieved and the cloud becomes a stable star. These early stages in a star's life probably take a few million years.



Large gas cloud condenses under gravity.



Balance between gravitational force and pressure is achieved.

Eventually the internal temperature of the star becomes high enough to sustain a nuclear reaction. It is by this process that a star "shines" for most of its lifetime. The nature of some of these reactions will be discussed in Unit 6 of course. For a star of solar mass, this evolutionary stage will require billions of years. This is the stage at which we see most of the stars in our night sky.

However, the stability of a star cannot last forever as it must eventually run out of nuclear fuel. It is during these later stages of stellar evolution that the force of gravity becomes dominant and may sometimes produce spectacular effects. Some stars when they become unstable in their later life implode under the force of gravity and then explode to become a supernova. The release of energy by a supernova explosion, equals the light from a million stars and scatters most of its mass into space. Such an explosion was reported by Chinese astronomers in 1000 B.C. and its remains are seen today as the Crab nebula. Other stars release matter into space by less spectacular methods.

The remaining star, having released much of its substance into space and no longer having fuel for a nuclear reaction, may at this stage finally yield to the force of gravity and undergo a collapse which will result in an extremely dense form of matter called a White Dwarf star. Densities of several tons per cubic inch, although unimaginable in terms of common substances on earth, are thought likely by theoretical astronomers. In fact some calculations suggest a complete stellar collapse resulting in a sphere of matter having a gravitational force so great that projectiles having speeds equal to that of light could not escape from its attraction. Because light would be trapped by such an object, it would be unobservable. These objects have been given the name *Black Holes* and are the subject of much speculation by astronomers, physicists, and science fiction writers. The later stages in a star's life occur in less than a few hundred million years. Astronomers are now in the process of trying to reconcile their theoretical predictions for a star's evolution with the evidence obtained from telescopic observations.

Scientists do not regard a law of physics as a final absolute answer, even though it may be useful to explain and predict observed phenomena. Scientific laws and theories are subjected to continuous testing which in many cases leads to their withdrawal from the list of scientific theories or perhaps their revision. As our perception of the universe has changed through the ages, so has our perception of nature's rules. This is part of the excitement of science. As we have seen, Newton's Law of Universal Gravitation is still used to describe many astronomical events. However, we no longer consider Newton's law as the correct description of gravity. Our view of gravity was changed in the twentieth century by the theories of

Albert Einstein whose modifications seem to account for some of the discrepancies in predictions made using Newton's law. One of the discrepancies was first recorded more than one hundred years ago.

In 1855, almost ten years after his discovery of Neptune, the astronomer Urbain Leverrier started a detailed analysis of the orbit of Mercury. He was attracted to Mercury because its orbit had an unexplained perturbation. This perturbation took the form of a slow revolution of the major axis of the orbit at a rate of about 1/100 degree per century. Since the perihelion point would also move at this rate the revolution is often referred to as a shift in the perihelion of Mercury.

In 1860, Leverrier presented a lecture to the Academy of Paris in which he suggested two possible solutions to this problem. Either the planet Venus was much heavier than the predicted value, or there was another planet orbiting the sun inside the orbit of Mercury. The first suggestion would have required an alteration in the mass of Venus by more than 10 percent and would have had a detectable influence on the earth's orbit. The second hypothesis initiated a search for an unknown planet which resulted in many apparently successful spottings. However, these apparent successes proved in many cases to be sunspots, stars or asteroids; the expected planet, named Vulcan, has never been observed. Therefore, scientists looked elsewhere for the unexplained shift in the perihelion of Mercury. Perhaps the law of gravity proposed by Newton did not correctly describe the motion of Mercury.

In his General Theory of Relativity, Albert Einstein offered a modification to Newton's law. This modification presented gravity from a new viewpoint and seemed to be verified by a few observations, one of which was the observed shift in the perihelion point of Mercury. Einstein's description introduced a new geometry of space not only involving our concepts of position but also of time. Newton's law is adequate for the prediction of most of the observed phenomena in our solar system and in the description of star systems. However, in some special situations, astronomers invoke the modification suggested by Einstein's General Theory of Relativity.

We end our biographical sketch of Isaac Newton by quoting Pope's epigram.

Nature and Nature's laws lay hid in night
God said, "Let Newton be!" and all was light.

To this has been added by an author unknown to us, the couplet:

It did not last. The devil laughing "Ho!
Let Einstein be!" restored the status quo.

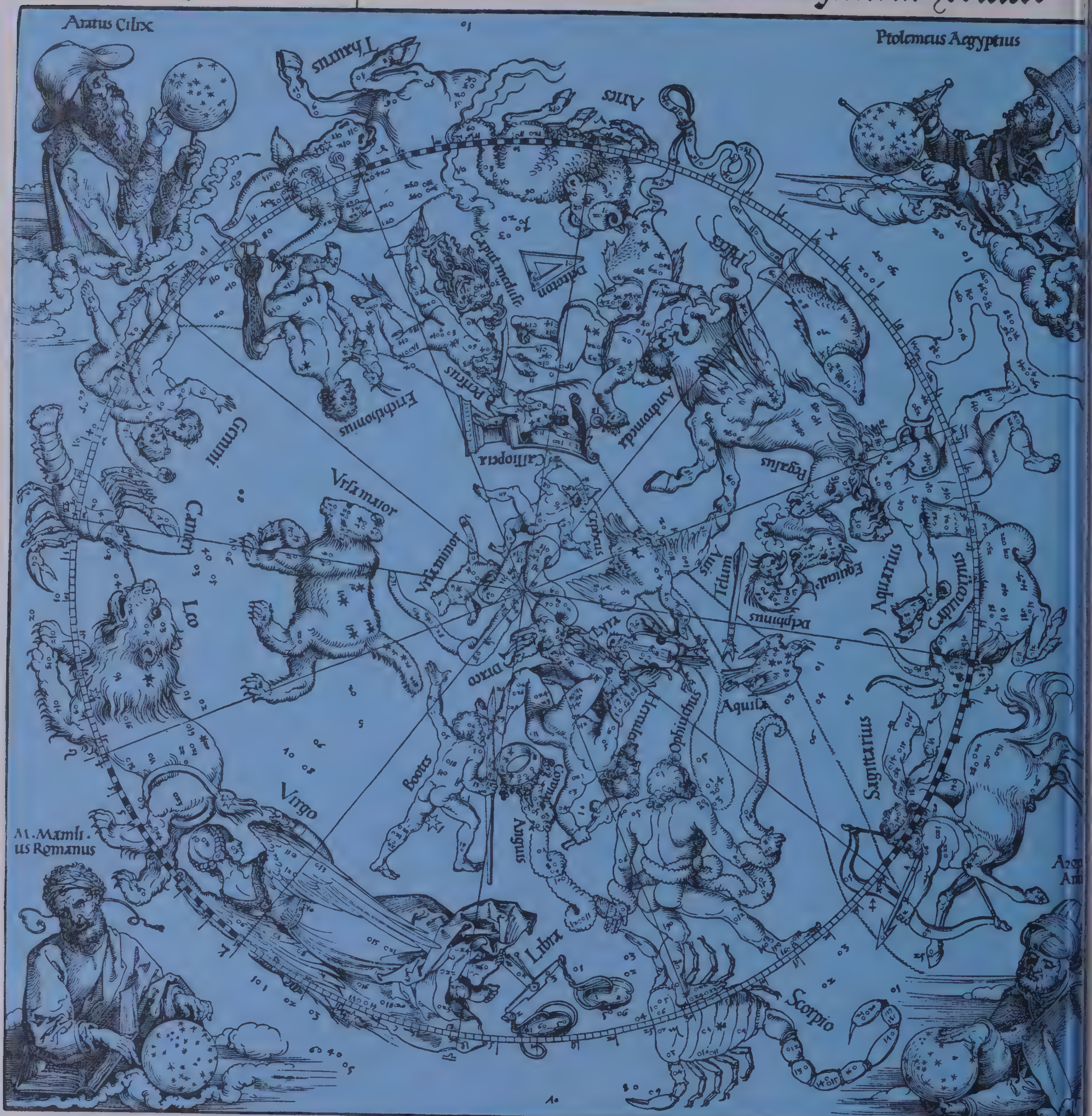
THE SOLAR SYSTEM

	RADIUS	MASS	AVERAGE RADIUS OF ORBIT	PERIOD OF REVOLUTION
Sun	6.95×10^8 metres	1.98×10^{30} kilograms	–	–
Moon	1.74×10^6	7.34×10^{22}	3.8×10^8 metres	2.36×10^6 seconds
Mercury	2.57×10^6	3.28×10^{23}	5.79×10^{10}	7.60×10^6
Venus	6.31×10^6	4.83×10^{24}	1.08×10^{11}	1.94×10^7
Earth	6.38×10^6	5.98×10^{24}	1.49×10^{11}	3.16×10^7
Mars	3.43×10^6	6.37×10^{23}	2.28×10^{11}	5.94×10^7
Jupiter	7.18×10^7	1.90×10^{27}	7.78×10^{11}	3.74×10^8
Saturn	6.03×10^7	5.67×10^{26}	1.43×10^{12}	9.30×10^8
Uranus	2.67×10^7	8.80×10^{25}	2.87×10^{12}	2.66×10^9
Neptune	2.48×10^7	1.03×10^{26}	4.50×10^{12}	5.20×10^9
Pluto	?	?	5.9×10^{12}	7.28×10^9

SATELLITES OF THE PLANETS

		DISCOVERY	AVERAGE RADIUS OF ORBIT	PERIOD OF REVOLUTION			DIAMETER
EARTH:	Moon		382,171 Km	27d	7h	43m	3456 Km
MARS:	Phobos	1877, Hall	9,300	0	7	39	16?
	Deimos	1877, Hall	23,400	1	6	18	8?
JUPITER:	V	1892, Barnard	181,000	0	11	53	240?
	1 (Io)	1610, Galileo	419,000	1	18	28	3200
	II (Europa)	1610, Galileo	667,000	3	13	14	2896
	III (Ganymede)	1610, Galileo	1,046,000	7	3	43	4988
	IV (Callisto)	1610, Galileo	1,872,000	16	16	32	4505
	VI	1904, Perrine	11,392,000	250	14		160?
	VII	1905, Perrine	11,664,000	259	14		56?
	X	1938, Nicholson	11,680,000	260	12		24?
	XII	1951, Nicholson	20,917,000	625			23?
	XI	1938, Nicholson	22,526,000	700			31?
	VIII	1908, Melotte	23,491,000	739			56?
	IX	1914, Nicholson	23,652,000	758			27?
SATURN:	Mimas	1789, Herschel	195,000	0	22	37	483?
	Enceladus	1789, Herschel	238,000	1	8	53	563
	Tethys	1684, Cassini	294,000	1	21	18	805
	Dione	1684, Cassini	377,000	2	17	41	805
	Rhea	1672, Cassini	526,000	4	12	25	1609
	Titan	1655, Huygens	1,222,000	15	22	41	4586
	Hyperion	1848, Bond	1,480,000	21	6	38	483?
	Phoebe	1898, Pickering	12,927,000	550			322?
	Iapetus	1671, Cassini	3,556,000	79	7	56	1287?
URANUS:	Miranda	1948, Kuiper	130,000	1	9	56	–
	Ariel	1851, Lassell	191,000	2	12	29	965?
	Umbriel	1851, Lassell	267,000	4	3	28	6433?
	Titania	1787, Herschel	438,000	8	16	56	1609?
	Oberon	1787, Herschel	586,000	13	11	7	1448?
NEPTUNE:	Triton	1846, Lassell	354,000	5	21	3	2781
	Nereid	1949, Kuiper	5,535,000	359	10		322?

Imagines coeli Septentrionales cum duodecim imaginibus zodiaci.



2

Handbook

Table of Contents

Preface

The purpose of this handbook is to provide you with some guidance in things which you can do in order to get some first-hand experience with the techniques of scientific investigation and the ideas and concepts of this physics course.

Unit 2 deals with the development of man's understanding of the Universe. The experiments provide a basis for becoming familiar with the heavens, and with some of the techniques and concepts developed by astronomers from very early times up to the use of the telescope. If your objective is to master basic astronomical techniques, you should try to do all of the experiments, and as many of the activities as possible. This will take considerable out-of-class time, but will be rewarding if you are interested. If, on the other hand, you want only to become acquainted with the theories, their development, and the people and circumstances which guided their development, you may omit some of the experiments. Ask your teacher for guidance in the choice of learning materials which would be best for you in this unit.

For the most part, there is a handbook section related to each chapter of the text. In each section there are usually three subsections: *Experiments, Activities,* and *Film Loop Notes.*

For each *Experiment,* instructions are outlined fully and may be followed by the entire class. In some cases alternate procedures are outlined and you may choose one or more on the bases of available equipment and personal preference.

At the end of some experiments are *Additional Questions* which may suggest further experimentation through which you could deepen your understanding or develop additional techniques.

In the *Activities* there are suggestions for mini-experiments, exercises, or projects which you can do in your own time. Detailed instructions for the activities are not usually given so that you may develop them by yourself in your own way.

Some film loops are recommended as part of this course. The *Film Loop Notes* provide some background about these loops and give instructions for their use.

Keeping Record of Laboratory Work

An essential part of doing laboratory work is the recording of results as the experiment proceeds. It is essential, because later, you or someone else will probably want to know what happened. In this section is some advice on how to keep a good record of your laboratory work. Your teacher may suggest a particular format for your reports, but, regardless of the type of record to be kept, there are some general principles which you should always try to follow.

1. Make your report sufficiently clear and complete so that months after its writing you will be able to pick up your report and from it explain to yourself or someone else exactly what happened.

2. Keep a complete record *as you do the experiment!* It is a bad habit to put data on a scrap of paper and then recopy them into your notebook later.

3. As you do the experiment, include in your record, answers to questions which occur to you or are given in the handbook. They are often important to your understanding of what is happening in the experiment.

A complete record usually contains the following parts.

Aim. You should know what you are trying to do before you start the experiment and should write your aim at the top of your report before you begin.

Apparatus. A good way to record what you use is to prepare a sketch of the apparatus. Label the main parts. List the types of equipment and any special settings or adjustments in case you wish to repeat the experiment at a later time.

Procedure. Outline the main points of what was done. Reference to the handbook for a description of the procedure may be adequate in some cases. (Such a reference would save some time.)

Observations. Organize all numerical data, if possible, in tabular form. Always identify the units, (metres, kilograms, seconds, etc.) for all of the data you record. If you suspect that a particular piece of data is not very reliable, (perhaps you measured it too quickly or the apparatus shifted), cross it out and make an explanatory note of the fact. Do not erase

the reading. You may find out later that it was correct after all and that you, not the data, were in error.

Analysis. Once you have collected the data you will interpret what they mean. Your analysis is the means by which you arrive at conclusions from your observations. While doing this analysis, do not ask, "What was supposed to happen?". Rather ask, "Based on my observation what must have happened?". In trying to answer this last question, show all steps of reasoning and calculation clearly.

A good graph often makes the meaning of your results much clearer. If you include graphs in your analysis, be sure that their form is correct and refer to their characteristics in drawing conclusions.

Include in the analysis, a discussion of sources of error or uncertainty and try to estimate how large each could be. If you want to take this calculation a step further, you could estimate the total uncertainty in your result due to the uncertainties in several separate factors.

Conclusions. *Conclusions must be based on your observations.* They should summarize what you learned from the experiment, not what you think "they" want (your teacher, the authors of the text . . . , or whoever). To relate conclusions to specific observations, a good format to use for a statement of a conclusion is, *since* . . . happened, *therefore* . . . must be true.

There is no "wrong" result in any experiment. If your observations and measurements are correct within the limitations of uncertainty, and your analysis is sound, then your results will be correct. Whatever happens in nature, including the laboratory, cannot be "wrong".

Joan Herman

Experiment 7.8 Satellite Orbit Nov 3

Aim: The aim of this experiment was to determine the shape of a satellite's orbit from a series of photos.

Apparatus and Procedure: See text p.236.

Observations: Measurements of the apparent diameter d of the satellite's disk from Dominion Observatory photographs are shown below:

Table 1

Date	d (m)	Satellite Longitude (degrees)	Data r (m)
June 1	0.12 ± 0.01	5 > 58	0.42 ± 8%
2	0.15	63 > 64	0.33
3	0.17	127 > 52	0.29
4	0.18	179 > 59	0.28
5	0.17	238 > 58	0.29
6	0.14	296 > 58	0.36
7	0.13	354 > 58	0.38
8	0.12	52	0.42

Analysis: To find the relative earth to satellite distance r for a scale diagram of the orbit, let

$$rd = 0.050\,m^2$$
$$r = \frac{0.050}{d}\,m$$

eg. for June 1, $d = (0.12 \pm 0.01)m = 0.12m \pm 8\%$

$$\therefore r = \frac{0.050}{0.12} = 0.42m \pm 8\%$$

All other values of r were calculated in the same way and recorded in Table 1.
The orbit plot is attached.

Q1 The satellite travels an average of

$$\frac{58+64+52+59+58+58+58}{7}$$

$$= 58°/\text{day}.$$

Its orbit period is $\frac{360}{58} = 6.2$ days.

Q2 Main sources of uncertainty in the experiment are:
a. measurement of d due to fuzzy edges in the photos.
b. longitude measurements because of uncertainty in where to place overlay on each photo.

Q3 The orbit shape is elliptical.

Additional Question
Q4 Using Kepler's Third Law

$$\frac{R_{moon}^3}{T_{moon}^2} = \frac{R_{satellite}^3}{T_{satellite}^2}$$

$$\therefore R_s^3 = \frac{T_s^2 \cdot R_m^3}{T_m^2}$$

$$= \frac{(6.2d)^2 \cdot (3.8 \times 10^5\,km)^3}{(27.2d)^2}$$

$$\therefore R_s = 1.4 \times 10^5\,km$$

Chapter 6. Where is the Earth?

In your study of astronomy you will want to locate objects in the sky and record their positions as you or others see them at various times and places. In order to do this, you will need to know the coordinate systems which are introduced in the experiments of this chapter.

Experiment 6.1 Naked-Eye Observations

The simplest method for locating an object, such as a star, is to measure its position in relation to your own horizon. First, you must establish a convenient reference point on the horizon. A point due north (N) of the observer is usually chosen. The reference point N is a point on the horizon directly under Polaris, the brightest star in the northern sky. To find Polaris follow a line from the two "pointers" in the constellation *Ursa Major* (the *Big Dipper*) as shown in Figure 6.1.

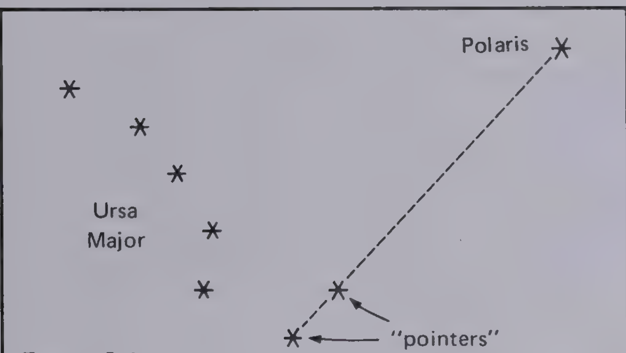


Figure 6.1

To specify the location of an object, first point to the reference point N, on your horizon, and then turn eastward until you are facing the object. *Measure the angle of rotation eastward along the horizon from N to a point on the horizon directly below the object.* This is the first coordinate of the object's location and is called its *azimuth.* In the example shown in Figure 6.2, the object's azimuth is 300 degrees.

Next, facing the object, *measure the angle vertically from the horizon plane to the object.* This angle is the second coordinate of the object's position and is called its *altitude.* In the example the object's altitude is 25 degrees.

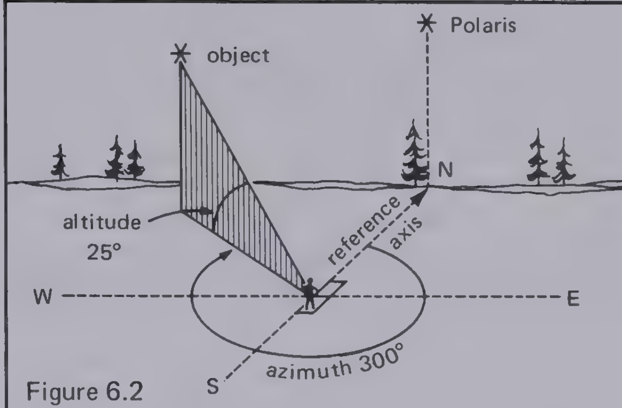


Figure 6.2

Q1 The directions north, east, south, and west have corresponding points on the observer's horizon called the *cardinal points* N, E, S, and W. These are shown in Figure 6.2. State the altitude and azimuth of each of the cardinal points.

Q2 The point in the sky directly above the observer is called the *zenith*. What is its altitude?

Q3 What is the azimuth of Polaris?

Procedure A Observation

On a clear night, go out into your backyard or, if you live in a brightly lit area, travel to a location where the background light is dim. If possible, take along an instrument to measure the objects' positions. (See Activity 6.1 Building an Astrolabe.)

MEASURING AZIMUTH AND ALTITUDE

First locate Polaris and establish the N point on your horizon. Mark it by a tree or some other prominent object along the horizon. Using an astrolabe, measure and record the altitude of Polaris.

Pick out other prominent objects such as the brightest stars in Ursa Major or in other constellations, the moon, and any planets which are visible. Measure the azimuth and altitude of each with a protractor and astrolabe. (A surveyor's transit is much more accurate if one is available.) Tabulate your results.

Repeat the measurements of the altitude and azimuth for some of the objects including Polaris at a later time (at least one hour later) the same evening and compare these with your earlier data.

Q4 Why do the altitude and azimuth of most objects change during the evening?
Q5 Within the limits of experimental uncertainty your measurements of the coordinates of Polaris should be unchanged. Why?
Q6 Based on your average measurement of the altitude of Polaris, what is your latitude? Compare your result with the value shown in an atlas. Find the percentage error in your result. This will indicate how accurate your other data is.
Q7 How would your results compare with those of an observer located at (a) the North Pole? (b) the Equator?

DIURNAL (DAILY) MOTION

As you have observed, the stars appear to move during the evening. This motion continues throughout the day and is called *diurnal* or *daily motion.* To find the rate of this motion follow the motion of stars near Polaris. The two "pointers" in Ursa Major can be used for this purpose. They are in a straight line with Polaris and rotate during the evening like the spoke of a wheel, taking different positions as shown in Figure 6.3.

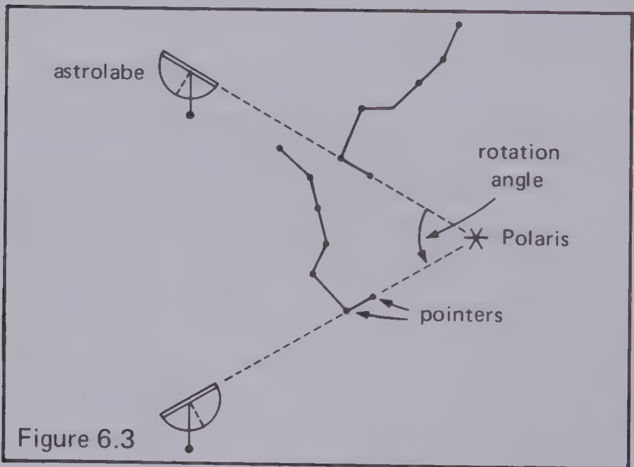


Figure 6.3

Sketch the position of Ursa Major and Polaris on a similar diagram of your own, as observed at two different times. Also, measure the angle through which the pointer line moved during this period of time. One way to do this is, at two different times, to hold an astrolabe as shown, with the sighting-tube lined up with the "pointers" and Polaris. Record the times and the angles.

Calculate the angle of rotation (a) for the observation period, (b) for one hour, (c) for one day.

Another method for measuring the daily motion, is to take a time-exposure photograph of the circumpolar region of the sky as outlined in Activity 6.2.

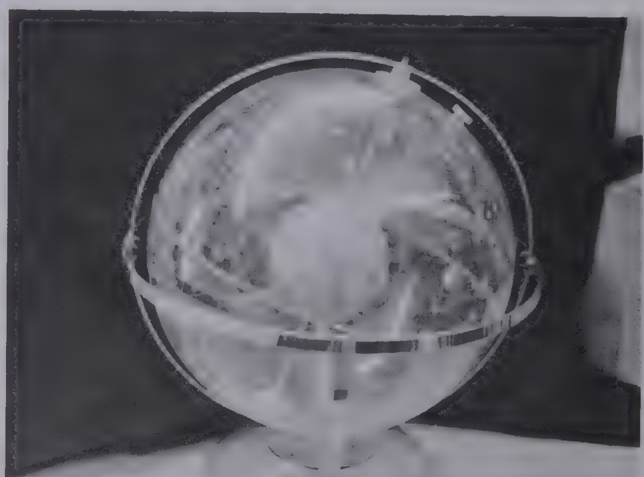
Q8 How can we tell that the stars and other celestial bodies continue to move at the same rate during daylight when they are invisible?
Q9 Why do some stars rise and some set during the evening?
Q10 Why do stars near Polaris neither rise nor set during the evening? Would these stars be up in the daytime?

Procedure B Using a Celestial Globe

Astronomers today find it convenient, as did the early Greeks, to think of the stars, planets, sun, and moon as if they were located on a celestial sphere with the earth at the centre. If a celestial globe is available (or you can make your own as shown in Activity 6.3 or 6.4), you can locate on the globe reference points and some of the objects which you observed in Procedure A.

On most celestial globes the fixed circle parallel to the base represents the observer's celestial horizon. The ring at right angles to the horizon represents the celestial meridian which in the observer's sky passes through his zenith, through Polaris, and through the N point on his horizon. The globe rotates on a polar axis which extends from the *North Celestial Pole* (NCP), which is very close to Polaris, through the centre of the sphere to the *South Celestial Pole* (SCP).

Figure 6.4



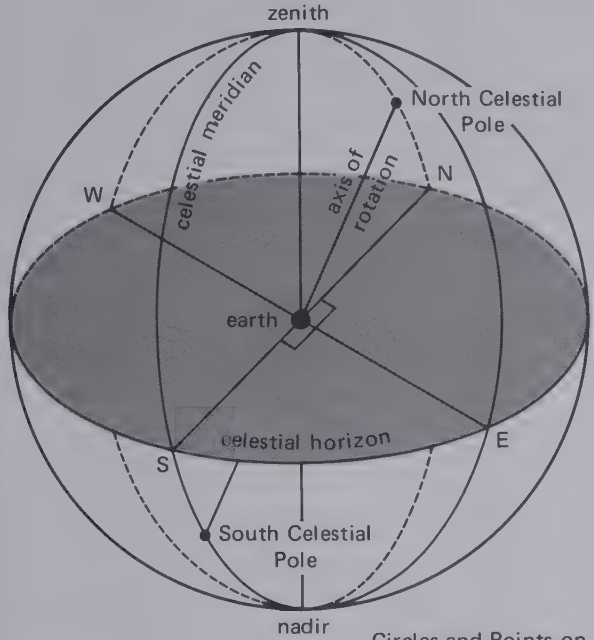


Figure 6.5 Circles and Points on the Celestial Globe

First, set the globe to represent the sky as seen from your location on earth. Since the altitude of Polaris is equal to your latitude, the axis of rotation should be set for your latitude. For example, since Calgary's latitude is 51 degrees North, the polar axis should be set at 51 degrees above the celestial horizon as shown in Fiqure 6.6.

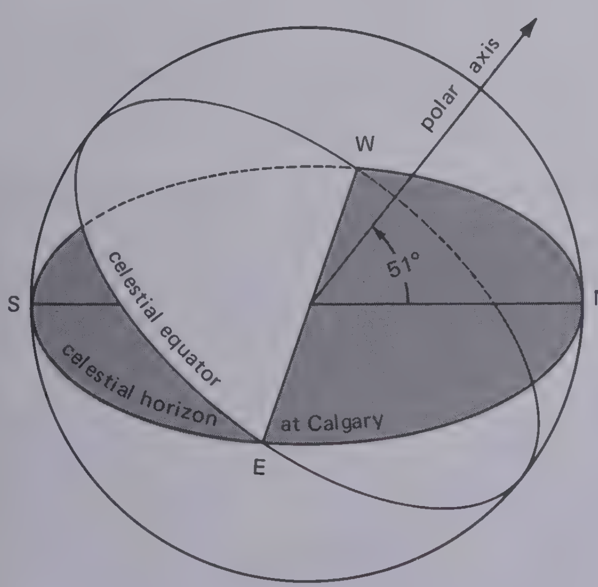


Figure 6.6

Next, mark the following locations on the globe.

(a) The observer's zenith
(b) The North and South Celestial Poles
(c) Polaris
(d) Several objects from your first measurements made in Procedure A
(e) Objects with azimuth and altitude shown in Table 6.1.

Table 6.1

Object	Azimuth (degrees)	Altitude (degrees)
A	0	–45
B	180	+45
C	90	–60
D(nadir)	–	–90
E	300	+25
F	300	–25
G	270	–60
H	90	+30

Q11 What portion of the globe can be seen by an observer on the earth as you have it set now?
Q12 Which objects from Table 6.1 will not be visible at this time? Why?

Now move the globe in a way corresponding to the daily motion of the sky.

Q13 In what way do objects move relative to the Earth's position (a) in a single day? (b) in one hour?

Set the globe at the position corresponding to the second set of your observations from Procedure A. For example, since the rate of the celestial sphere's daily motion is 360 degrees/day = 15 degrees/hour, if your second set of coordinates were measured 2 hours after the first, you would rotate the globe 30 degrees westward from the first setting.

From the globe, determine the azimuth and altitude of the objects for a second setting and compare each with the coordinates of these objects measured in Procedure A. Use an example to illustrate your explanation.

Q14 How would you use the globe to find the azimuth and altitude of an object, six hours after your first observation? Use an example to illustrate your explanation.

Q15 How can you explain the rising and setting of stars using the globe?

Additional Questions

Q16 The azimuth and altitude of a star change in a predictable way with time. How can you use the coordinates of a star to determine the time?

Q17 The azimuth and altitude of a star, at a certain time, depend on the location of the observer. This is one principle upon which navigation of ships and planes is based. Find out how navigators measure and use the positions of stars to determine their position. One reference is *Exploration of the Universe* by C. Abell, published by Holt, Rinehart and Winston.

Experiment 6.2 Motion of the Sun

The sun is the easiest object to follow in the sky, not only because it is much brighter than any other, but also because for most locations in Canada it is visible almost every day. In this experiment you will study the sun's motion over a period of one day (sunrise to sunset) and one year. You may not be able to make all of the observations yourself. This is not uncommon among astronomers either. They depend to a great extent on observations recorded by colleagues in other locations at other times. For example, in his *Almagest* Ptolemy recorded positions of 1028 stars and these positions were used for fourteen hundred years. Tables of data showing the sun's position are available, but if possible you should make your own observations for your own location. To make your own observations of the sun's altitude and azimuth, you can use the apparatus shown.

Never look directly at the sun. It can cause permanent eye damage in a few seconds.

Procedure A Sun Observations for One Day

Any clear day will do, although certain special days such as the *vernal equinox* (Mar. 21), the *autumnal equinox* (Sept. 23), the *summer solstice* (June 21), or the *winter solstice* (Dec. 21) are particularly interesting. You will need a large portion of the day free to make these observations, so arrange with your teacher beforehand. Table 6.2 shows data obtained by a student in Ottawa on Sept. 15. If you cannot obtain your own data, use the results in Table 6.2 and proceed directly to the analysis.

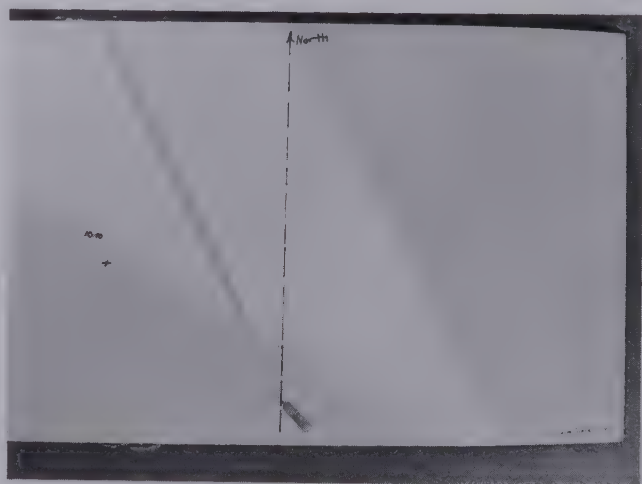
Table 6.2

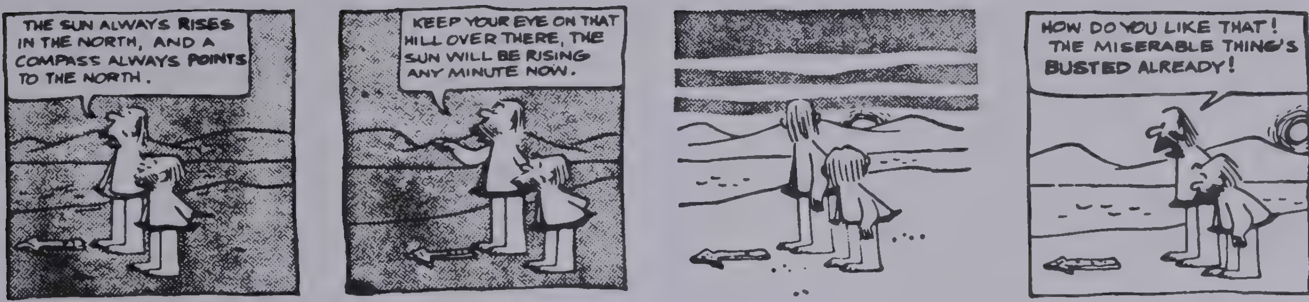
Eastern Daylight Time (EDT)	Sun's Azimuth (degrees)	Sun's Altitude (degrees)
8:00 a.m.	99	13
9:00	110	23
10:00	124	33
11:00	139	40
12:00	159	46
1:00 p.m.	180	48
2:00	202	46
3:00	221	40
4:00	237	32
5:00	250	23
6:00	261	12
7:00	268	2

First, a reference axis pointing true north must be marked ahead of time as shown in Experiment 6.1.

Azimuth. To measure the sun's azimuth angle, prepare a sheet of paper with a reference axis as shown in Figure 6.7. Polar graph paper would be best for this experiment. Tape it to a board or cardboard. Drive a long finishing nail or T-pin perpendicular to the paper at one end of the reference axis. Place the board on a level portion of ground or on a level table. This device is called a gnomon (nō-mŏn). Align the

Figure 6.7





reference axis to point due north. The N point on your horizon which you established in Experiment 6.1 can be used. (If you did not do this, use a compass, although it will not give as accurate measurements.)

At regular time-intervals (every hour would be satisfactory) mark the end of the sun's shadow. At the end of the day, measure the sun's azimuth for each shadow. Remember that the sun's position is directly opposite from its shadow. This means that if the sun's shadow at 1:00 p.m. is 5 degrees clockwise from the reference axis, the sun's azimuth is 185 degrees as shown in Figure 6.8. Tabulate your data in a table similar to Table 6.2.

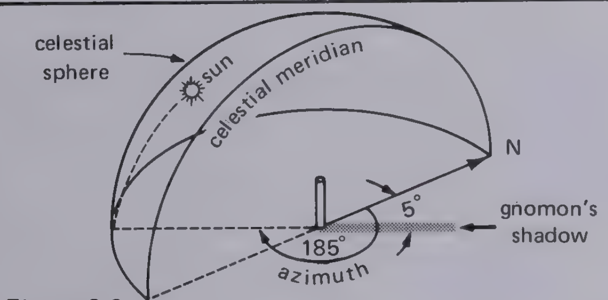


Figure 6.8

Altitude. To measure the sun's altitude, you can use an instrument called an *astrolabe.* Details for constructing your own astrolabe are given in Activity 6.1. For stability attach the astrolabe to a tripod as shown in Figure 6.9. Slip a piece of cardboard over the end of the sighting-tube which is to be pointed toward the sun.

Do not look at the sun! Instead, project the sun's rays passing through the sighting-tube onto a paper screen. Adjust the angle of the astrolabe until the image is a bright circle on the middle of the screen as shown in Figure 6.10.

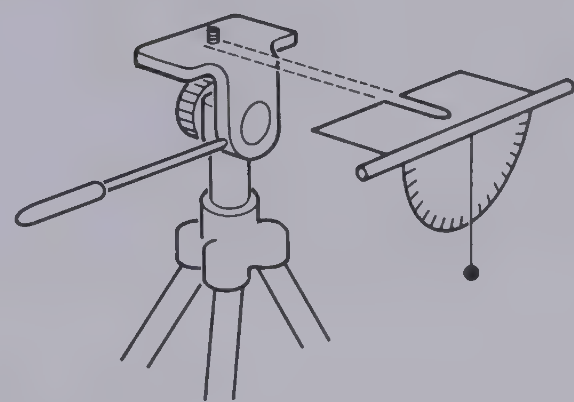


Figure 6.9

Measure and tabulate the altitude for the same times as for the azimuth angles.

Analysis

Plot the sun's altitude (on the vertical axis) versus azimuth (on the horizontal axis). It is not necessary to begin the azimuth scale at 0 because in the northern hemisphere the sun never rises due north. Instead, begin at around 70 degrees.

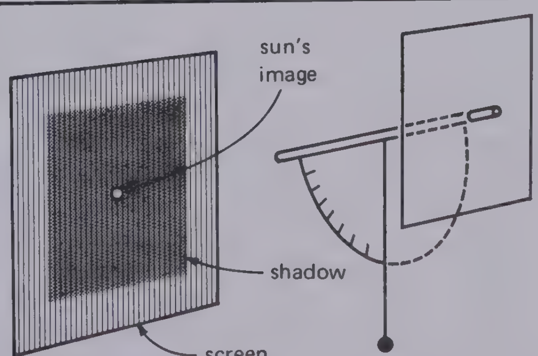


Figure 6.10

Q1 What is the sun's maximum altitude for this day?
Q2 At what time is the sun's altitude maximum on this day?
Q3 For most observers the sun's maximum altitude does not occur exactly at 12:00 noon. How can you explain this?
Q4 What is the sun's azimuth when its altitude is maximum for any day? How could you determine the correct direction of the reference axis from the sun's motion?
Q5 Examine the rate of change of the sun's azimuth. When is it changing most quickly? When is it changing most slowly? Why is the rate of change not constant?
Q6 What is the average change in the sun's azimuth per hour? How much would the sun's azimuth change in one day (24 hours)?
Q7 At what time of year would you predict the sun's noon altitude would be (a) maximum? (b) minimum? Explain.
Q8 From your graph, determine the sunrise and sunset azimuth. (The sun is on the horizon at sunrise or sunset.) From these results estimate the sunrise and sunset times and check them with the newspaper.

Another interesting curve to study is the curve through the end points of the sun's shadow on your gnomon paper. Compare characteristics of this curve with the azimuth-altitude graph.

Q9 At what time of day is the sun's shadow shortest? Why? What is its direction at this time?
Q10 Sketch the shadow-line you would expect if the gnomon were set up at (a) the North Pole, (b) a position on the equator, on the same day as your observations.

Procedure B Sun Observations for One Year

To study the sun's yearly motion, you can obtain sufficient data by measuring the sun's altitude at monthly intervals.

Measure the sun's maximum altitude as outlined in Procedure A at or near noon at the same time of each month for as much of the year as possible. Also measure the azimuth of the sunset point. (Sunrise is too early for most of us!) Find out the times for sunrise and sunset. You may consult your local newspaper, a radio station, or *The Observer's Handbook* which is published annually by the Royal Astronomical Society of Canada, 252 College St., Toronto.

Tabulate your data in a table similar to Table 6.3.

If it is not practical for you to make your own observations, you can use the data provided in Table 6.3.

Analysis

Plot the sun's maximum altitude (on the vertical axis) versus the date (on the horizontal axis). Also plot, all

Table 6.3
Sun observations for one year at Windsor (latitude 42° N), Jan. 21 to Dec. 21.

Date	Sun's maximum altitude (degrees)	Sunset azimuth (degrees)	Sunrise time E.S.T. (hr	min)	Sunset time E.S.T. (hr	min)
Jan. 21	28	241	7	22	17	00
Feb. 21	37	256	6	48	17	39
Mar. 21	48	271	6	02	18	14
Apr. 21	60	286	5	10	18	48
May 21	68	298	4	34	19	20
June 21	71	302	4	24	19	40
July 21	68	298	4	42	19	30
Aug. 21	60	286	5	14	18	52
Sept. 21	49	271	5	46	18	00
Oct. 21	37	256	6	20	17	09
Nov. 21	28	243	6	57	16	34
Dec. 21	25	238	7	25	16	32

Figure 6.12

on the same sheet of graph paper, graphs of the sunset azimuth, sunrise time, and sunset time versus the date. Use a different colour or distinguishing mark for each graph. Draw the "best fit" curve for each and use your graph to answer the following questions.

Q11 At what time of year was the sun's noon altitude (a) maximum? (b) minimum?
Q12 (a) When was the longest day? (The day when the sun was above the horizon for the longest time.) (b) When was the shortest day?
Q13 Why is the sunset azimuth maximum when the sun's altitude is greatest?
Q14 For what dates is the sun (a) farthest north? (b) farthest south? (c) directly over the equator?
Q15 What is the range in degrees of the sun's maximum altitude for a year? Explain using a diagram.
Q16 Use your graphs to find the sun's maximum altitude, sunset azimuth, sunrise time, and sunset time on Nov. 5.
Q17 Use your observations to explain the seasons in the northern hemisphere.

Additional Questions

Q18 Using the fact that the sun is directly over the equator on the equinoxes as shown in Figure 6.11,

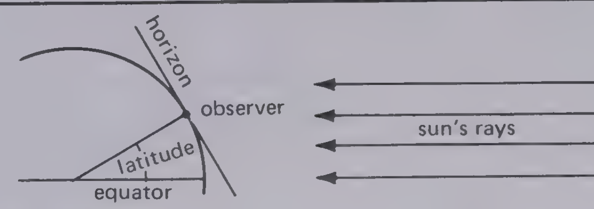


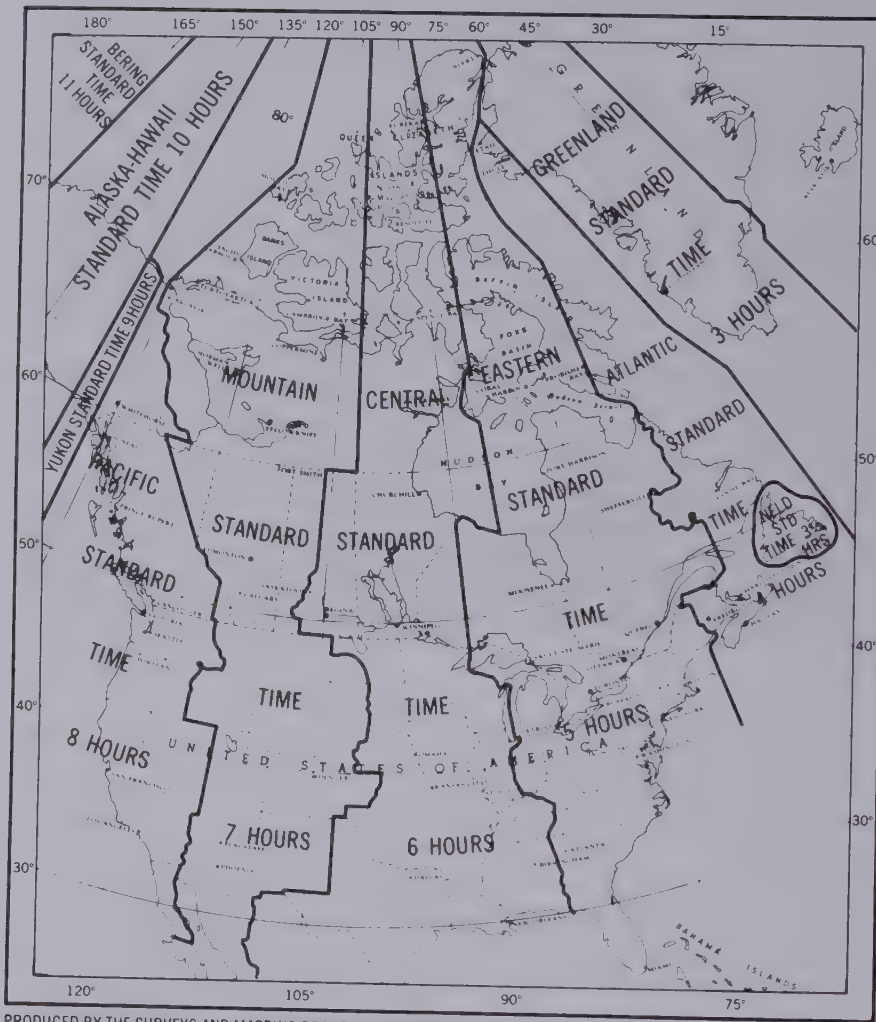
Figure 6.11

explain how to find the observer's latitude from a measurement of the sun's maximum altitude on the equinoxes. (A sketch similar to Figure 6.11 is helpful.)

Q19 What type of behaviour do you expect from the shadow-line created by the gnomon for an observer at the equator
(a) before the autumnal equinox (Mar. – Sept.)?
(b) on Sept. 23?
(c) after the autumnal equinox (Sept. – Mar.)?
Q20 Figure 6.12 is a photograph of the sun taken at 5-minute intervals over the Ross Sea in Antarctica. The sun's diameter is approximately ½ degree.

This is an example of the midnight sun. Explain this phenomenon using diagrams of the celestial sphere. Also consider what the sun's motion would be a few days earlier and a few days later, observed at the same location.

MAP OF STANDARD TIME ZONES



PRODUCED BY THE SURVEYS AND MAPPING BRANCH, DEPARTMENT OF ENERGY, MINES AND RESOURCES, OTTAWA, CANADA, 1972.

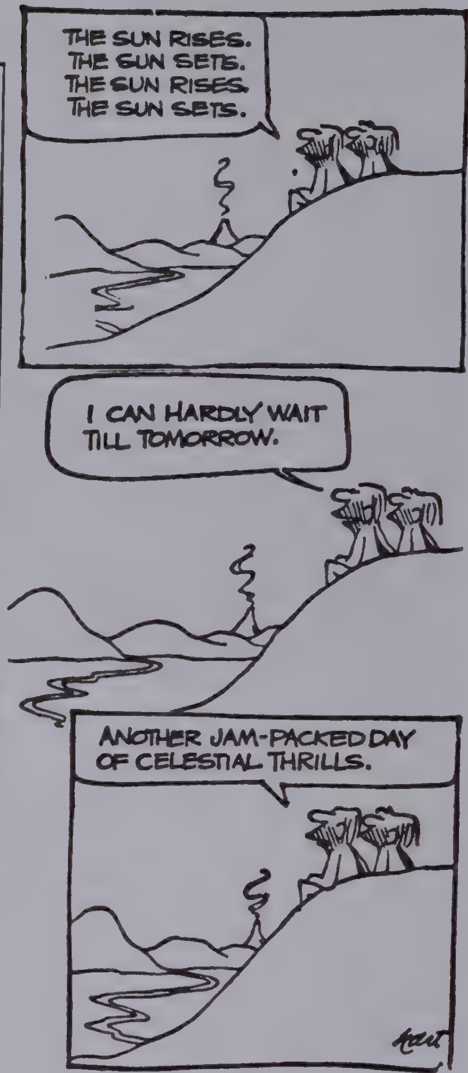


Figure 6.13

Q21 Since the sun's location changes with time in a predictable way, the sun can be used to tell time as shown in Activity 6.5. As part of this pattern, the sun reaches its maximum altitude for every observer exactly at local noon. However, this time may not be exactly 12:00 noon by the clock for each observer. The difference in local noon times for two different locations depends on the difference in their longitude on the earth. For example, the sun is directly overhead at Montreal (longitude 73°W) 24 minutes before it is in Toronto (longitude 79°W). The difference in longitude is 6 degrees. Since the sun moves 15 degrees westward every hour, we can see that in the 24 minutes, the sun would move $\frac{24}{60} \times 15° = 6°$ westward, just the difference in longitude between Montreal and Toronto. The earth is divided into time zones each one hour earlier than the next, westward across the map as shown in Figure 6.13. The sun is directly over the 0° longitude line at exactly 12:00 noon Greenwich Mean Time. One hour later it will be directly over the 15°W line of longitude. Five hours later it will be directly over the 75°W line of longitude at exactly 12:00 noon Eastern Standard Time which will be 5:00 p.m. Greenwich Mean Time and 9:00 a.m. Pacific Standard Time.

Study the time-zone map and use your observations of the sun's local noontime to determine your longitude. If you have a contact in another location (preferably in another time zone), have him do the same experiment and find the difference in your longitudes. Check your results with an atlas.

Experiment 6.3 The Celestial Sphere — Equator Coordinate System

From studying the motions of the sun and stars, it is probably clear to you that although the horizon coordinate system is easy to use, it is limited because the azimuth-altitude coordinates of an object change with the position of the observer and with time.

In this experiment you will use a second coordinate system, the *Equator Coordinate System* which is outlined in the text. In it, an object's location is specified by two coordinates on the celestial sphere:

Right Ascension (RA) is measured along the celestial equator in hours or degrees (1h ≡ 15°) eastward from the vernal equinox (intersection of the ecliptic and the celestial equator). On the diagram this reference point sometimes called the *first point of Aries*, is represented by the symbol ♈.

Declination is measured in degrees north (+) or south (−) of the celestial equator.

For example the location of *Capella* has coordinates: RA, 5 h 15 min (78.5°), and declination, + 47 degrees as shown in Figure 6.14.

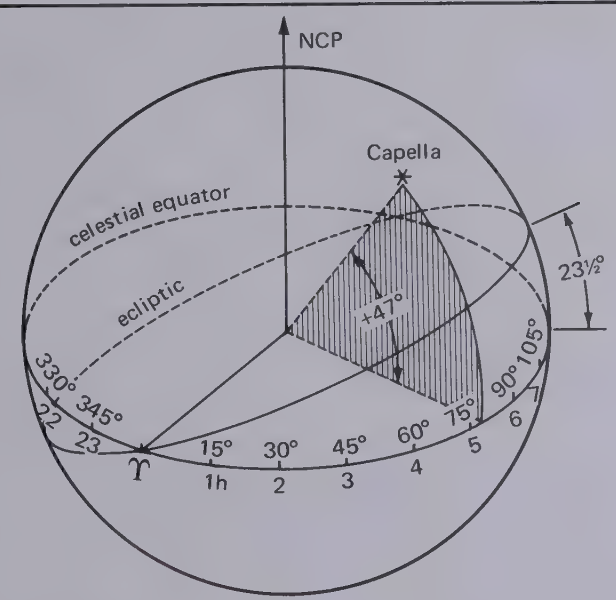


Figure 6.14

To become more familiar with the equator coordinate system you will find and plot the locations of several objects on a celestial globe or a flat star map, a more convenient method of representing the sky.

Procedure A Finding Coordinates

The Sun's Path. Since the sun moves through the sky along the ecliptic, you will need its location on several dates during the year. First, find the right ascension (RA) and declination of the sun on the equinoxes and the solstices and tabulate your results as shown in Table 6.4.

Table 6.4
The Sun's Position Through the Year

Date	RA		Declination
	(hours)	(degrees)	(degrees)
Vernal Equinox Mar. 21			
Autumnal Equinox Sept. 23			
Summer Solstice June 21			
Winter Solstice Dec. 21			

To find more points along the ecliptic use your data for the yearly motion of the sun from Experiment 6.2 in the following way: On the vernal equinox, the sun is at the intersection of the celestial equator and the ecliptic so that its declination is zero. A few days later, it has moved above the equator so that its observed maximum altitude is greater. The change in the sun's maximum altitude from its value on the equinox to that on a particular date is the same as its declination on that date. For example, in Table 6.3 the sun's maximum altitude on May 21 is 68 degrees and only 48 degrees on the equinox, Mar. 21. Therefore, based on these observations, the sun's declination on May 21 is (68 − 48) degrees = 20 degrees. Find the declination for several dates in the same way and record the results in your table. To find the sun's RA for the same dates, remember that the sun moves 360 degrees (24 hours) eastward along the ecliptic in one year or approximately 1 degree per day. Starting from the vernal equinox, you can count off days to determine the RA of the sun for each of the dates in Table 6.4.

STAR POSITIONS

Table 6.5 contains a list of RA and declination for some of the brighter stars near the Celestial Equator. The colour and distance to the star in light years

Table 6.5
Stars in the Equatorial Region

Star	RA	Declination	Colour	Distance
Vega	18 h 36 m	+ 38° 45′	white	26.5 l.y.
Betelgeuse	5 53	+ 7 24	red	520.0
Procyon	7 37	+ 5 19	white	11.3
Sirius	6 44	– 16 40	blue-white	8.7
Rigel	5 13	– 8 14	blue-white	900.0
Canopus	6 23	– 52 40	white	104.
Arcturus	14 14	+ 19 21	orange	220.0
Fomalhaut	22 56	– 29 48	white	22.6

Table 6.6
Stars in the North Circumpolar Region

Star	RA	Declination	
Vega	18h 36m	+ 38° 45′	
Polaris	02 02	+ 89 08	
Capella	05 15	+ 45 58	
Deneb	20 40	+ 45 10	
α Ursa Major	11 02	+ 61 55	
β " "	11 00	+ 56 33	
γ " "	11 52	+ 53 52	These are the brightest stars in Ursa Major (Big Dipper).
δ " "	12 14	+ 57 12	
ϵ " "	12 53	+ 56 07	
τ " "	13 23	+ 55 05	
η " "	13 46	+ 49 28	

(l.y.) are also shown. (One l.y. is the distance travelled by light, which has a velocity of 3.0×10^8 m/s, in one year.) Table 6.6 lists stars in the northern sky around Polaris.

Consult a star catalogue or *The Observer's Handbook* to find coordinates of several more bright stars in each region. Record the coordinates in tables similar to Tables 6.5 and 6.6.

Procedure B Plotting on the Celestial Globe

Obtain a celestial globe or chalk globe, or make your own as shown in Activities 6.3 or 6.4.

If you are using your own globe or a chalk globe, mark on the celestial equator. Choose a reference point on the equator and label it ♈ to indicate the first point of Aries. Mark off the equator in 24 equal divisions. Each division will represent 1 hour or 15 degrees of R.A. Label an RA scale eastward (to the right) from ♈. Next, draw a great circle from the NCP through ♈ and around the globe back to the NCP. Divide this circle in 12 equal divisions each representing 30 degrees of declination. Number these (0, 30, 60, 90) starting from the equator, and moving to the poles in each direction. Complete your globe by drawing a spherical grid: great circles through the poles to intersect the equator at the hour marks (these are called *hour circles*) and the circles parallel to the equator at the declination divisions. Figure 6.15 shows roughly how your globe should look.

The Ecliptic. Using the right ascension and declination for each of the sun's positions in Table 6.4, locate these points and draw the ecliptic on the globe. Label the equinoxes and solstices.

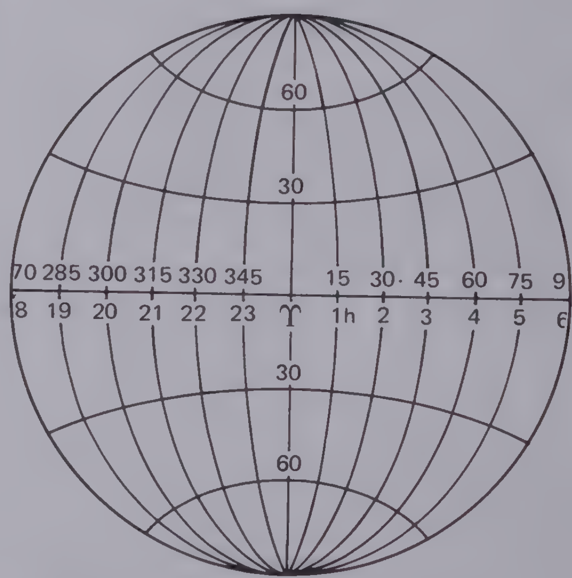


Figure 6.15

The Stars. Locate, and label on the globe, the stars' positions from Tables 6.5 and 6.6.

Q1 What happens to the RA and declination of a star during the celestial sphere's diurnal motion? Why?

Q2 Are all stars with negative declination always below the horizon? Explain.

Procedure C Plotting on Star Maps

Flat maps which are projections of the celestial sphere are used to represent the heavens in the same way as road maps show the curved surface of the earth. The celestial sphere can be broken down into circumpolar and equatorial regions as shown in Figure 6.16.

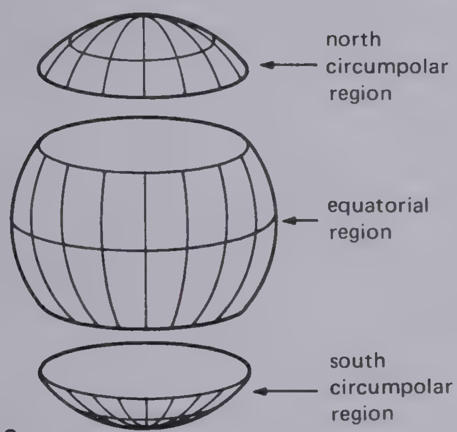


Figure 6.16

For the equatorial region, set up the coordinate axes on a sheet of graph paper. Plot the RA horizontally and the declination vertically on axes like those in Figure 6.17.

Notice that on the map eastward is to your left, because you are looking toward the inside of the celestial sphere from the earth, rather than from the outside in as you are doing when using the celestial globe.

Using coordinates from Table 6.4, plot the ecliptic on the map. Mark the equinoxes and solstices and label them with dates. Also plot the positions of stars from Table 6.5 on the map.

To see how accurate your map is, you can compare with the *SC 1 Constellation Chart (SC 1* and *SC 2 Constellation Charts* are available from Sky Publishing Corporation, 49 Bay State Road, Cambridge, Mass., U.S.A.) or a similar star map. You will see the stars grouped in constellations. Note the constellations containing the stars in Table 6.5 and if you have time include these on your map.

List the constellations along the ecliptic. These comprise the *Zodiac* and throughout the year the sun, moon, and planets move across it.

Q3 During what month(s) is the sun in Aquarius, Gemini, Libra?

To show the polar regions, a circular form of map is used. A piece of polar graph paper would be useful,

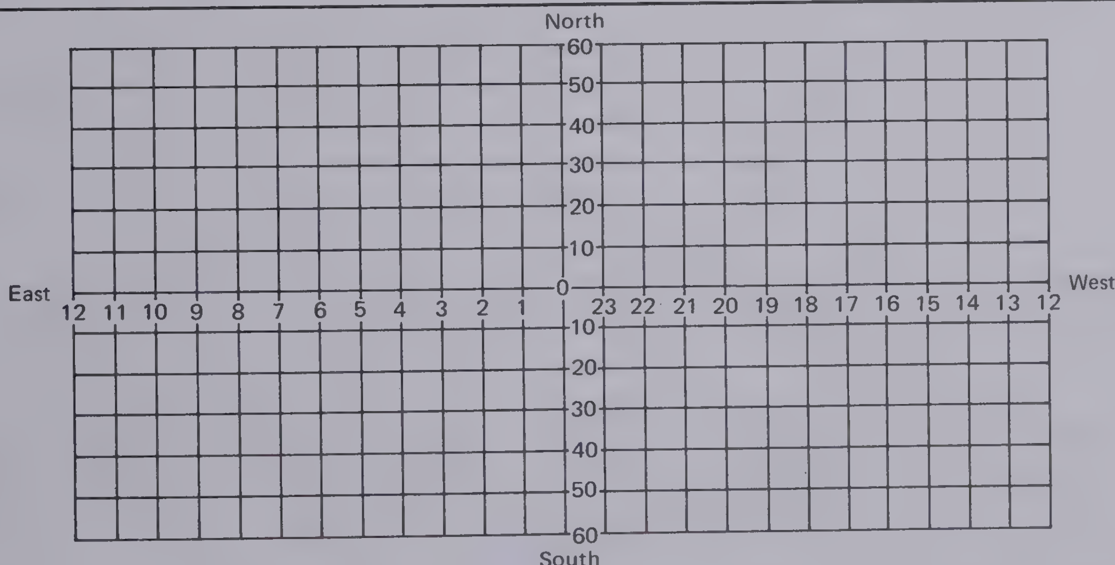
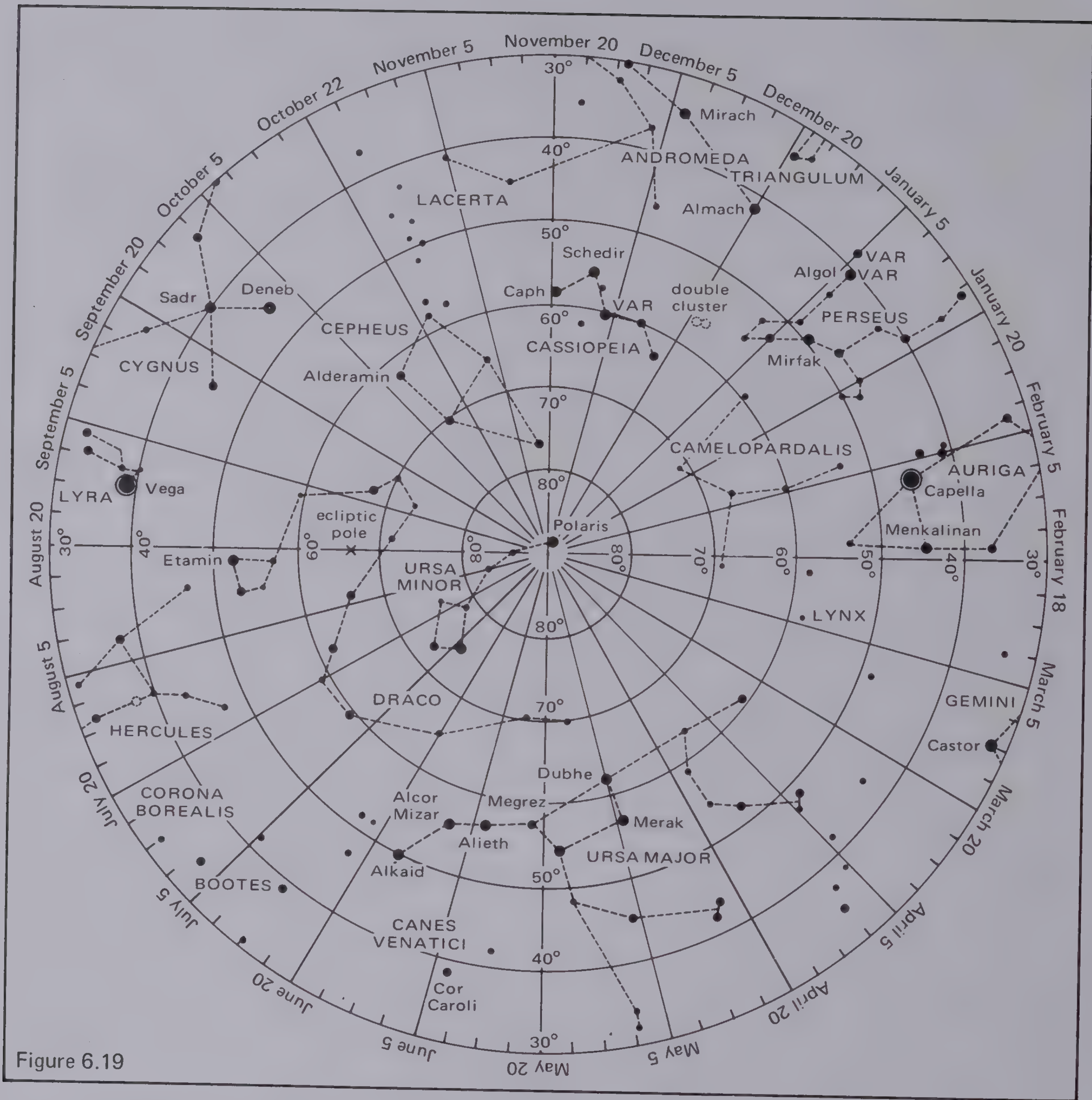


Figure 6.17


November 5
November 20
December 5
December 20
January 5
January 20
February 5
February 18
March 5
March 20
April 5
April 20
May 5
May 20
June 5
June 20
July 5
July 20
August 5
August 20
September 5
September 20
October 5
October 22
30°
40°
50°
60°
70°
80°
Mirach
ANDROMEDA
TRIANGULUM
Almach
LACERTA
Schedir
Caph
VAR
double cluster
CASSIOPEIA
CEPHEUS
Alderamin
Algol
VAR
VAR
PERSEUS
Mirfak
CAMELOPARDALIS
AURIGA
Capella
Menkalinan
Sadr
Deneb
CYGNUS
LYRA
Vega
Etamin
ecliptic pole
Polaris
URSA MINOR
LYNX
DRACO
GEMINI
Castor
HERCULES
CORONA BOREALIS
Dubhe
Alcor
Mizar
Megrez
Merak
Alieth
Alkaid
URSA MAJOR
BOOTES
CANES VENATICI
Cor Caroli
Figure 6.19


IT IS MY PROFOUND CONVICTION THAT THE WORLD IS ROUND, INSTEAD OF FLAT!
LIKE, WE'RE RIGHT HERE!
NOW!—WE SAIL ALL THE WAY AROUND TO HERE—
THEN, WE FALL OFF.

but if none is available, you can make your own axes and circles to form a grid like the one in Figure 6.18.

Locate the stars given in Table 6.6 on your polar region map.

Compare your map with a copy of the *SC 2 Constellation Chart* or the star map in Figure 6.19. Fill in other circumpolar constellations if you have time.

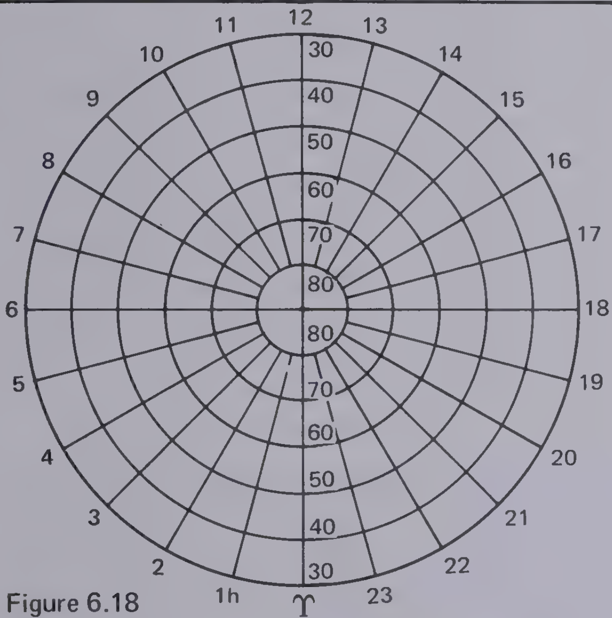


Figure 6.18

Observing

These star maps can be used as a guide if you know how to orient them properly. To use the polar map, locate Polaris and face north. If using *SC 2* or Figure 6.19, turn the chart until today's date is at the top. Then place the map overhead. The stars should be in the positions shown at 8 p.m. For every hour before 8 p.m. rotate the map one sector (15 degrees) clockwise. For every hour after 8 p.m. rotate the map one sector counterclockwise. These movements correspond to the diurnal motion of the celestial sphere.

To use the equatorial map, you must first find the equator in the sky. You can do this roughly by pointing with one arm directly at Polaris and swinging your other arm in a circle perpendicular to your pointing arm. This should sweep out the equatorial region of the sky covered by part of your equatorial map. The *SC 1* map is dated so that it can also be aligned by facing north with the map turned so that today's date is northward. Part of the equatorial region will be below your horizon and other parts will set during the evening. Rotate the map at 15 degrees per hour to compensate.

Try to identify as many bright stars as possible. Note their colours are different as shown in Table 6.5. Also identify the polar constellations. Most of these should be visible under good observing conditions. Look for constellations along the ecliptic (slightly above or below the equator).

You will not fail to see the moon if it is up. Also, you may notice one or more very bright objects along the ecliptic — brighter than any other stars. These will not be marked on *SC 1* or *SC 2*. They are planets and their position is not fixed on the celestial sphere. Further observing sessions to watch their progress would be interesting.

Additional Questions

Q4 How can you convert from the horizon coordinates of a celestial object to the equatorial coordinates?
This is a rather complicated operation but if you have a celestial globe available, it can be used as a calculator. A procedure for doing this is outlined in Huffer, Marasso, *Laboratory Exercises in Introductory Astronomy*, Holt, Rinehart and Winston, 1967. Exercise 3, pages 16-22.

Experiment 6.4 Motions of the Moon

The moon is the brightest object in the night sky. Its nature and behaviour have fascinated man for thousands of years and have yielded important data which have helped us understand the nature of the solar system.

In this experiment you will observe the moon, and use data to reach conclusions about its motion.

Procedure

Diurnal Motion. The moon's diurnal motion is similar to that of the sun. Verify this by making observations of the moon's position at regular intervals during one evening. An alternative method is to photograph the moon with a fixed camera, exposing the same film at regular intervals during the evening.

Plot a graph of the moon's altitude versus its azimuth. Use the graph to determine the rising and setting times and compare with actual times for that day. Compare the moon's diurnal motion with the sun's.

Monthly Motion. The moon's monthly motion can be studied by recording its position every evening, or as often as possible for an entire month. Each evening, at the same time just after sunset, observe and record the moon's altitude and azimuth. Note the evenings which you must miss; a few missed will not affect the results.

At least once a week, note the phase of the moon and estimate the angle between the sun and the moon.

Show the angle between the sun and moon, and the moon's apparent shape in each case as shown in Figure 6.20.

If you are unable to make suitable observations, use the data in Table 6.7 made in Saskatoon, Saskatchewan (latitude 52°N). Negative values were calculated from observations later the same night after the moon had risen.

Plot a graph of altitude versus azimuth near sunset for the moon's motion.

From your data or graph, estimate the dates of the new moon, full moon, first quarter, and third quarter.

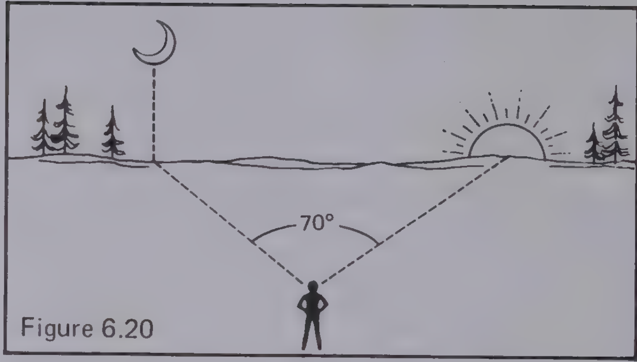


Figure 6.20

Label these points on the graph. The photographs in Figure 6.21 show the moon in various phases.

Q1 In how many days does the moon complete one revolution?
Q2 Through how many degrees approximately does the moon move on the celestial sphere in 24 hours?
Q3 How much earlier or later does the moon rise each successive evening? Why?
Q4 Why is the graph not a closed curve?

PLOTTING THE MOON'S ORBIT ON A STAR MAP

In Table 6.8 are the RA and declination of the moon for a one-month period during October and November 1972. The data were taken from the *American Ephemeris and Nautical Almanac* available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, U.S.A.

Table 6.7

Position of the Moon observed at Saskatoon. **Date: Jan./Feb. 72**

Date	Moon's altitude near sunset (degrees)	Moon's azimuth near sunset (degrees)	Angle between sun and moon (degrees)	Moon's maximum altitude (degrees)
	10 p.m. E.S.T.	10 p.m. E.S.T.		
Jan. 7	−25	110	257	34
9	−44	124	281	23
11	−59	149	306	15
13	−64	199	330	11
15	−51	239	354	13
17	−28	259	29	21
19	9	266	53	32
21	20	257	78	46
23	44	241	102	57
25	62	206	126	64
27	61	147	151	64
29	43	116	175	58
31	21	101	200	53
Feb. 2	0	91	224	42
4	−20	98	248	30

Table 6.8

Date	RA	Declination	Phase
Oct. 7, 1972	12h29m	− 8° 27′	new moon
9	14 01	−17 32	
11	15 39	−23 40	
13	17 23	−25 40	
15	19 08	−23 01	first quarter
17	20 50	−15 57	
19	22 31	− 5 28	
21	0 14	+ 6 46	full moon (22)
23	2 08	+18 03	(Hunter's Moon)
25	4 15	+24 48	
27	6 24	+24 36	
29	8 21	+18 18	last quarter
31	10 02	+ 8 39	
Nov. 2	11 33	− 2 03	
4	13 03	−12 07	
6	14 36	−20 08	new moon

Figure 6.21

Use the equatorial region map showing the ecliptic which you plotted in Experiment 6.3. On this map, plot the moon's position for October and November 1972.

Show the sun's progress along the ecliptic during the same period.

Q5 From your map, determine how many degrees above and below the ecliptic the moon's declination ranges. (In 1978 the plane of the moon's orbit will be 5° below the ecliptic plane. In 1968 the moon's orbit was inclined 5° above the ecliptic. These are maximums in the difference between declination of the sun and moon.)

Q6 Why do eclipses not occur at least once a month?

Experiment 6.5 The Planets

Five of the planets, Mercury, Venus, Mars, Jupiter, and Saturn can be observed without a telescope. The various times at which they are prominent in the sky

Table 6.9
Planet Longitudes at 10-Day Intervals

Yr.	Date	J.D.	☉	☿	♀	♂	♃	♄
		2440000						
1973	SEP 24	1950	181	198	223	40	302	94
1973	OCT 4	1960	191	213	235	38	302	94
1973	OCT 14	1970	201	226	246	36	302	95
1973	OCT 24	1980	211	235	257	32	303	94
1973	NOV 3	1990	221	236	268	27	304	94
1973	NOV 13	2000	231	224	278	25	305	94
1973	NOV 23	2010	241	222	288	24	306	93
1973	DEC 3	2020	251	232	297	25	308	93
1973	DEC 13	2030	261	246	304	26	310	92
1973	DEC 23	2040	272	262	309	28	312	91
1974	JAN 2	2050	282	278	313	32	314	90
1974	JAN 12	2060	292	294	311	37	317	89
1974	JAN 22	2070	302	311	306	41	319	88
1974	FEB 1	2080	312	328	300	46	321	87
1974	FEB 11	2090	322	341	296	51	324	87
1974	FEB 21	2100	332	340	297	57	326	87
1974	MAR 3	2110	342	330	301	63	329	87
1974	MAR 13	2120	352	327	308	68	331	88
1974	MAR 23	2130	2	335	316	73	333	88
1974	APR 2	2140	12	346	325	79	335	89
1974	APR 12	2150	22	1	335	85	337	89
1974	APR 22	2160	32	18	346	91	340	90
1974	MAY 2	2170	42	38	357	97	342	91
1974	MAY 12	2180	51	61	8	103	343	93
1974	MAY 22	2190	61	80	19	109	345	94
1974	JUN 1	2200	70	94	31	115	346	95
1974	JUN 11	2210	80	102	42	121	347	96
1974	JUN 21	2220	89	103	54	128	347	97
1974	JUL 1	2230	99	97	66	134	348	99
1974	JUL 11	2240	109	94	77	140	348	100
1974	JUL 21	2250	118	97	89	146	347	102
1974	JUL 31	2260	128	110	101	152	348	103
1974	AUG 10	2270	137	129	114	159	347	104
1974	AUG 20	2280	147	150	126	165	345	105
1974	AUG 30	2290	157	169	139	171	344	106
1974	SEP 9	2300	166	185	151	177	342	106
1974	SEP 19	2310	176	200	163	184	341	107
1974	SEP 29	2320	186	212	176	191	339	108
1974	OCT 9	2330	196	220	188	197	338	108
1974	OCT 19	2340	206	219	201	204	338	109
1974	OCT 29	2350	216	207	213	211	337	109
1974	NOV 8	2360	226	207	226	218	338	109
1974	NOV 18	2370	236	218	238	224	338	109
1974	NOV 28	2380	246	234	251	231	339	109
1974	DEC 8	2390	256	250	264	238	340	108
1974	DEC 18	2400	266	266	276	245	341	108
1974	DEC 28	2410	276	281	289	253	342	107
1975	JAN 7	2420	287	298	301	260	344	105
1975	JAN 17	2430	297	314	314	267	346	104
1975	JAN 27	2440	307	325	326	274	348	103
1975	FEB 6	2450	317	322	339	281	350	103
1975	FEB 16	2460	327	312	351	289	353	102
1975	FEB 26	2470	337	312	4	296	355	102
1975	MAR 8	2480	347	320	16	304	357	102
1975	MAR 18	2490	357	332	28	312	0	102
1975	MAR 28	2500	7	347	41	319	2	102
1975	APR 7	2510	17	5	53	327	5	103
1975	APR 17	2520	27	25	65	334	7	103
1975	APR 27	2530	36	46	76	342	9	104
1975	MAY 7	2540	46	65	88	349	12	105
1975	MAY 17	2550	56	78	99	357	14	106
1975	MAY 27	2560	65	83	110	4	17	107
1975	JUN 6	2570	75	81	120	12	18	108
1975	JUN 16	2580	84	75	131	19	20	110
1975	JUN 26	2590	94	74	140	27	21	111
1975	JUL 6	2600	103	82	148	33	22	112
1975	JUL 16	2610	113	96	155	40	24	114
1975	JUL 26	2620	123	115	160	47	24	115
1975	AUG 5	2630	132	137	162	54	24	116
1975	AUG 15	2640	142	156	160	60	25	117
1975	AUG 25	2650	151	172	154	66	25	118
1975	SEP 4	2660	161	187	149	72	24	119
1975	SEP 14	2670	171	198	145	77	23	120
1975	SEP 24	2680	181	205	146	82	22	121
1975	OCT 4	2690	190	202	150	86	21	122
1975	OCT 14	2700	200	190	156	90	19	122
1975	OCT 24	2710	210	192	164	92	18	123
1975	NOV 3	2720	220	205	174	93	16	123
1975	NOV 13	2730	230	221	184	92	15	123
1975	NOV 23	2740	240	237	194	89	14	123
1975	DEC 3	2750	251	253	206	87	14	123
1975	DEC 13	2760	261	269	217	83	14	123
1975	DEC 23	2770	271	285	229	79	14	122
1976	JAN 2	2780	281	300	241	76	15	122
1976	JAN 12	2790	291	310	253	74	16	121
1976	JAN 22	2800	302	304	265	73	18	120
1976	FEB 1	2810	312	294	277	74	19	119
1976	FEB 11	2820	322	296	289	77	21	118
1976	FEB 21	2830	332	306	302	80	22	117
1976	MAR 2	2840	342	319	314	83	24	117
		2440000						
1976	MAR 12	2850	352	334	326	87	27	116
1976	MAR 22	2860	2	352	339	92	29	116
1976	APR 1	2870	12	11	351	97	31	116
1976	APR 11	2880	22	32	4	102	33	116
1976	APR 21	2890	31	51	16	107	36	117
1976	MAY 1	2900	41	61	28	112	39	118
1976	MAY 11	2910	51	63	41	117	41	118
1976	MAY 21	2920	60	58	53	123	44	119
1976	MAY 31	2930	70	54	65	128	46	120
1976	JUN 10	2940	79	56	78	134	48	121
1976	JUN 20	2950	89	66	90	140	50	122
1976	JUN 30	2960	99	82	102	146	52	123
1976	JUL 10	2970	108	101	114	152	54	124
1976	JUL 20	2980	118	123	127	158	56	126
1976	JUL 30	2990	127	143	139	164	58	127
1976	AUG 9	3000	137	159	152	171	59	129
1976	AUG 19	3010	146	173	164	177	60	130
1976	AUG 29	3020	156	185	176	183	61	131
1976	SEP 8	3030	166	188	189	190	61	132
1976	SEP 18	3040	175	183	201	196	61	133
1976	SEP 28	3050	185	174	213	203	61	134
1976	OCT 8	3060	195	177	225	210	60	135
1976	OCT 18	3070	205	191	237	216	60	136
1976	OCT 28	3080	215	208	249	223	58	137
1976	NOV 7	3090	225	225	262	230	58	137
1976	NOV 17	3100	235	241	274	237	56	137
1976	NOV 27	3110	245	257	286	244	54	138
1976	DEC 7	3120	256	272	298	252	53	137
1976	DEC 17	3130	266	286	309	259	52	137
1976	DEC 27	3140	276	294	321	267	51	137
1977	JAN 6	3150	286	287	332	274	50	136
1977	JAN 16	3160	296	277	343	281	50	135
1977	JAN 26	3170	306	282	354	289	51	134
1977	FEB 5	3180	317	292	3	297	51	134
1977	FEB 15	3190	327	306	12	305	53	133
1977	FEB 25	3200	337	321	19	312	54	132
1977	MAR 7	3210	347	339	23	320	55	131
1977	MAR 17	3220	357	358	25	328	57	131
1977	MAR 27	3230	7	18	22	335	59	130
1977	APR 6	3240	16	36	16	343	60	130
1977	APR 16	3250	26	45	10	351	63	130
1977	APR 26	3260	36	43	7	359	65	131
1977	MAY 6	3270	46	36	9	7	67	131
1977	MAY 16	3280	55	34	13	15	69	132
1977	MAY 26	3290	65	40	20	22	72	133
1977	JUN 5	3300	74	52	28	30	74	133
1977	JUN 15	3310	84	68	38	37	77	134
1977	JUN 25	3320	94	87	48	44	79	135
1977	JUL 5	3330	103	110	58	51	81	136
1977	JUL 15	3340	113	129	69	58	83	137
1977	JUL 25	3350	122	146	80	65	85	138
1977	AUG 4	3360	132	159	91	72	87	140
1977	AUG 14	3370	141	168	103	79	89	141
1977	AUG 24	3380	151	171	114	85	91	143
1977	SEP 3	3390	161	164	126	92	93	144
1977	SEP 13	3400	170	157	138	97	94	145
1977	SEP 23	3410	180	162	150	103	95	146
1977	OCT 3	3420	190	178	162	108	95	147
1977	OCT 13	3430	200	196	175	113	96	148
1977	OCT 23	3440	210	212	187	118	96	149
1977	NOV 2	3450	220	229	200	122	96	150
1977	NOV 12	3460	230	244	213	126	95	150
1977	NOV 22	3470	240	259	225	129	95	151
1977	DEC 2	3480	250	272	238	131	93	151
1977	DEC 12	3490	260	278	251	132	92	151
1977	DEC 22	3500	271	269	263	131	91	151
1978	JAN 1	3510	281	261	276	128	89	151
1978	JAN 11	3520	291	267	288	125	88	151
1978	JAN 21	3530	301	279	301	121	87	150
1978	JAN 31	3540	311	293	313	117	86	149
1978	FEB 10	3550	321	309	326	114	86	148
1978	FEB 20	3560	331	326	338	112	86	147
1978	MAR 2	3570	341	344	351	111	86	146
1978	MAR 12	3580	351	4	3	112	86	146
1978	MAR 22	3590	1	20	16	114	87	145
1978	APR 1	3600	11	27	28	117	88	144
1978	APR 11	3610	21	22	41	120	90	144
1978	APR 21	3620	31	15	53	124	91	144
1978	MAY 1	3630	41	16	66	128	93	144
1978	MAY 11	3640	50	24	78	133	95	144
1978	MAY 21	3650	60	36	90	138	97	145
1978	MAY 31	3660	69	53	102	143	99	146
1978	JUN 10	3670	79	74	114	148	101	146
1978	JUN 20	3680	89	96	126	153	103	147
1978	JUN 30	3690	98	116	137	159	106	148
1978	JUL 10	3700	108	132	149	165	108	149
1978	JUL 20	3710	117	144	160	171	110	150
1978	JUL 30	3720	127	152	171	177	112	151
1978	AUG 9	3730	136	152	182	183	115	152
1978	AUG 19	3740	146	144	192	189	117	153
		2440000						
1978	AUG 29	3750	156	140	202	196	119	155
1978	SEP 8	3760	165	147	211	202	121	156
1978	SEP 18	3770	175	164	219	209	122	157
1978	SEP 28	3780	185	183	227	216	124	159
1978	OCT 8	3790	195	200	231	222	125	160
1978	OCT 18	3800	205	217	234	229	127	161
1978	OCT 28	3810	215	232	232	237	128	162
1978	NOV 7	3820	225	246	227	244	128	162
1978	NOV 17	3830	235	258	221	251	129	163
1978	NOV 27	3840	245	262	218	258	129	163
1978	DEC 7	3850	255	252	220	266	129	164
1978	DEC 17	3860	265	245	224	273	128	164
1978	DEC 27	3870	275	253	231	281	128	164
1979	JAN 6	3880	286	266	240	289	126	164
1979	JAN 16	3890	296	281	249	297	125	164
1979	JAN 26	3900	306	297	259	304	123	163
1979	FEB 5	3910	316	313	270	312	122	163
1979	FEB 15	3920	326	331	281	320	121	162
1979	FEB 25	3930	336	349	293	328	120	162
1979	MAR 7	3940	346	5	304	336	119	161
1979	MAR 17	3950	356	9	316	344	119	159
1979	MAR 27	3960	6	1	328	352	119	159
1979	APR 6	3970	16	355	340	359	119	158
1979	APR 16	3980	26	359	352	7	120	158
1979	APR 26	3990	36	9	3	15	121	158
1979	MAY 6	4000	45	22	15	23	121	158
1979	MAY 16	4010	55	39	27	30	123	158
1979	MAY 26	4020	64	60	40	38	124	158
1979	JUN 5	4030	74	82	52	45	126	159
1979	JUN 15	4040	84	102	64	52	128	159
1979	JUN 25	4050	93	117	76	59	130	160
1979	JUL 5	4060	103	129	89	66	132	161
1979	JUL 15	4070	112	134	101	74	134	162
1979	JUL 25	4080	122	132	113	81	136	163
1979	AUG 4	4090	131	125	126	87	138	164
1979	AUG 14	4100	141	123	138	94	140	165
1979	AUG 24	4110	151	133	150	100	143	166
1979	SEP 3	4120	160	150	163	107	145	167
1979	SEP 13	4130	170	170	175	113	147	168
1979	SEP 23	4140	180	188	188	119	149	170
1979	OCT 3	4150	190	205	200	125	151	171
1979	OCT 13	4160	199	220	212	131	153	172
1979	OCT 23	4170	209	233	225	136	154	173
1979	NOV 2	4180	219	243	237	141	156	174
1979	NOV 12	4190	229	246	250	146	157	175
1979	NOV 22	4200	240	234	262	151	158	175
1979	DEC 2	4210	250	230	275	155	159	176
1979	DEC 12	4220	260	239	288	158	159	176
1979	DEC 22	4230	270	253	300	161	160	177
1980	JAN 1	4240	280	269	312	164	160	177
1980	JAN 11	4250	290	284	324	165	160	178
1980	JAN 21	4260	301	301	336	165	159	177
1980	JAN 31	4270	311	318	349	163	158	177
1980	FEB 10	4280	321	335	1	161	157	177
1980	FEB 20	4290	331	349	12	157	155	176
1980	MAR 1	4300	341	351	24	153	154	176
1980	MAR 11	4310	351	341	36	150	153	175
1980	MAR 21	4320	1	337	46	147	152	174
1980	MAR 31	4330	11	343	57	146	151	173
1980	APR 10	4340	21	354	67	145	150	172
1980	APR 20	4350	30	8	76	147	150	172
1980	APR 30	4360	40	26	84	149	150	171
1980	MAY 10	4370	50	46	89	152	151	171
1980	MAY 20	4380	59	68	92	156	151	171
1980	MAY 30	4390	69	88	92	160	152	172
1980	JUN 9	4400	79	102	87	164	153	172
1980	JUN 19	4410	88	112	80	169	154	173
1980	JUN 29	4420	98	115	75	174	156	173
1980	JUL 9	4430	107	111	74	179	157	174
1980	JUL 19	4440	117	105	77	185	159	175
1980	JUL 29	4450	126	107	83	191	161	175
1980	AUG 8	4460	136	118	91	197	163	176
1980	AUG 18	4470	145	136	99	203	165	177
1980	AUG 28	4480	155	157	109	210	167	178
1980	SEP 7	4490	165	175	119	216	169	179
1980	SEP 17	4500	175	192	130	223	171	180
1980	SEP 27	4510	184	207	141	229	174	182
1980	OCT 7	4520	194	220	152	236	176	183
1980	OCT 17	4530	204	228	164	244	178	184
1980	OCT 27	4540	214	229	176	251	180	185
1980	NOV 6	4550	224	217	188	258	182	186
1980	NOV 16	4560	234	215	200	266	184	187
1980	NOV 26	4570	244	226	212	273	185	187
1980	DEC 6	4580	255	241	225	281	187	188
1980	DEC 16	4590	265	256	237	288	187	189
1980	DEC 26	4600	275	272	250	296	188	189

J. D. stands for Julian Days. Julian Day 1 was chosen arbitrarily as one day in 4713 BC. (September 24, 1973 is J. D. 2,441,950.)

can be obtained from *The Observer's Handbook* or the magazine, *Sky and Telescope**. Since the planes of the planetary orbits lie very close to the ecliptic plane (never more than 8° above or below it), their motions on the celestial sphere lie almost along the ecliptic.

ECLIPTIC COORDINATE SYSTEMS

A third coordinate system, particularly useful for indicating the positions of the planets, uses the ecliptic as the basic circle along which celestial longitude is marked off in degrees eastward from ♈. Celestial latitude is measured in degrees above (+) or below (−) the ecliptic, as shown in Figure 6.22.

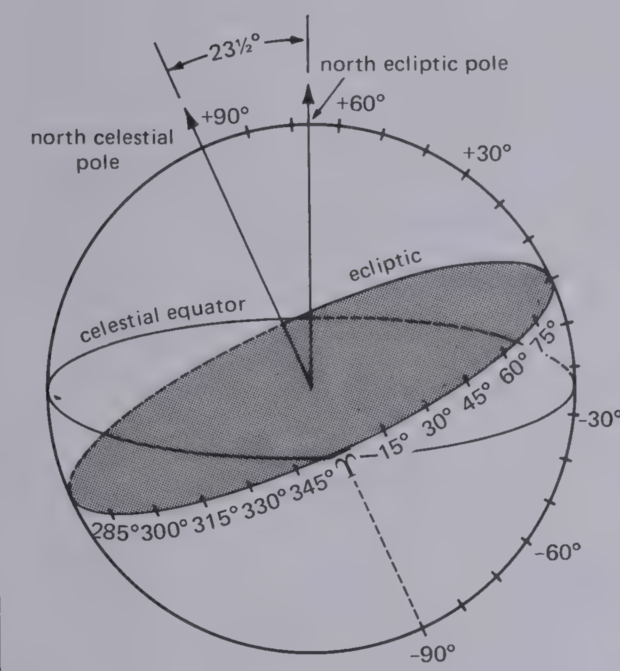


Figure 6.22

PLANETARY POSITIONS

Table 6.9 gives the longitudes of the planets and sun at 10-day intervals.

Plot the planets' positions for your date on the equatorial region of your constellation chart (*SC 1* or the star map which you constructed in Experiment 6.3).

**Sky and Telescope* is a magazine useful for amateur astronomers and published by Sky Publishing Corporation, 49 Bay State Road, Cambridge, Mass., U.S.A.

Now, by comparing longitudes of the sun with those of the planets, determine roughly which planet(s) should be visible. If a planet's longitude is close to that of the sun, it will rise and set during the day with the sun, and will therefore, be invisible in the bright sky. If its longitude is 180° east of the sun, it will rise as the sun sets and be visible.

Q1 Which planet(s) should be visible for your date? Why? Compare your conclusions with the information in *The Observer's Handbook* or *Sky and Telescope.*

Study the planetary longitudes and you will see that the longitude increases as the planet moves eastward, then decreases as it reverses direction in retrograde motion.

Q2 What two planets are in retrograde motion in November 1973? Would you be able to observe the retrograde motion? Why?

Q3 Find several dates of retrograde motion for each planet. Compare the sun's and planet's longitude during retrograde motion. For what planetary position relative to the sun will retrograde motion generally occur for (a) Jupiter, Mars, or Saturn (outer planets)? (b) Mercury or Venus (inner planets)?

GRAPHING PLANETARY MOTION

Along the Ecliptic. You can analyse the planet's motion relative to the sun by plotting a graph of longitude versus date. First, plot the sun's longitude versus date to give straight line segments as shown in Figure 6.23.

On the same axes plot the longitude of Mercury and Mars. Use your graphs to answer these questions.

Q4 Why is the sun's graph almost a straight line?

Q5 What is the maximum deviation of Mercury's longitude from that of the sun? (This is called its maximum elongation.)

Q6 How can you tell when a planet is in retrograde motion from the graph?

Q7 What is the significance of points where a planet's curve crosses (a) the sun's line? (b) another planet's curve?

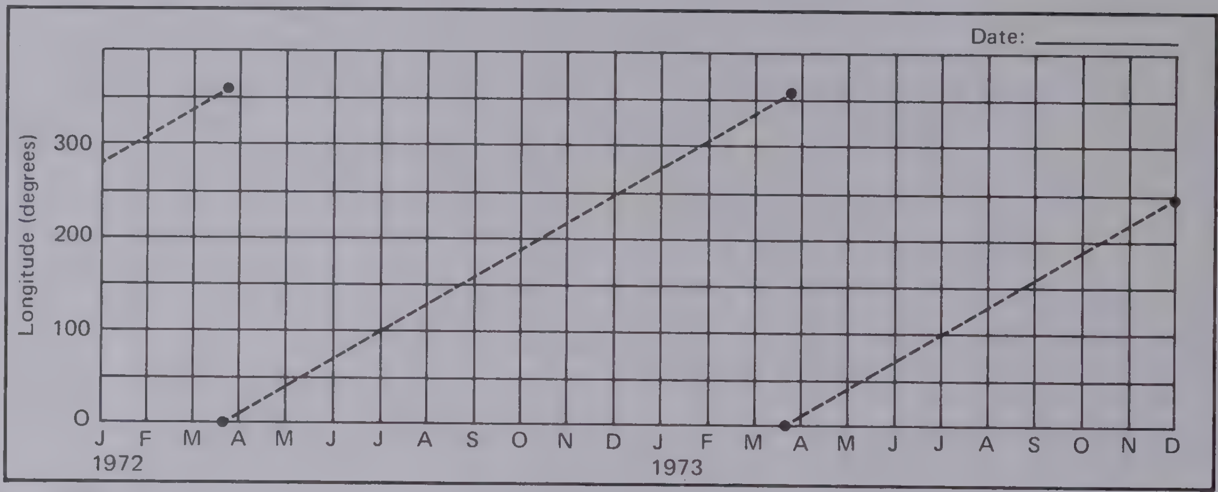


Figure 6.23

Table 6.10
Positions of Mars and Venus
(taken from *American Ephemeris and Nautical Almanac)*

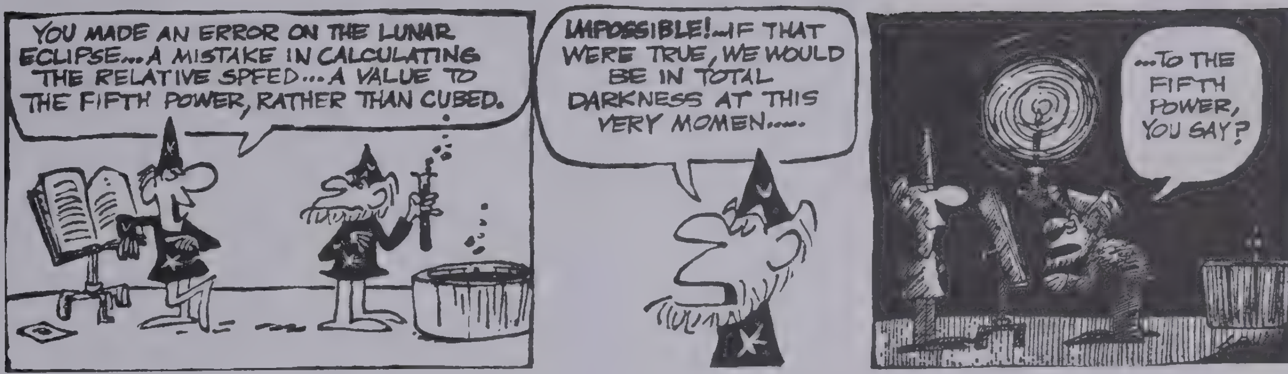
Mars			Venus		
Date	**RA**	**Declination**	**Date**	**RA**	**Declination**
May 22, 1971	20h48m	−20° 16′	May 1, 1972	5h33m	+27° 30′
June 1	21 05	−19 36	11	6 51	+27 33
11	21 21	−19 06	22	6 19	+26 48
21	21 33	−18 50	June 1	6 19	+25 29
July 1	21 41	−18 54	11	6 02	+23 30
11	21 45	−19 21	21	5 36	+21 04
21	21 43	−20 11	July 1	5 16	+18 59
31	21 37	−21 13	11	5 11	+17 59
Aug. 10	21 27	−22 13	21	5 20	+17 59
21	21 15	−22 57	31	5 43	+18 31
31	21 08	−23 05	Aug. 10	6 13	+19 07
Sept. 10	21 04	−22 41	21	6 53	+19 25
20	21 06	−21 48	31	7 33	+19 04
30	21 14	−20 33			
Oct. 11	21 26	−18 49			
21	21 41	−16 58			
31	21 59	−14 53			

On the Celestial Globe. Table 6.10 gives RA and declination for Venus and Mars during retrograde motion. Plot these data either on a celestial globe or on a star map. Replot on graph paper to show the motion in more detail.

Q8 Explain why the particular retrograde motion of Venus shown in Table 6.10 is a reversal, whereas that of Mars is a crossover (loop)?

OBSERVING THE PLANETS

During an observing session locate the visible planets with the aid of your constellation chart. Mark each planet's position on the chart. If you are able to watch for several evenings, plot each planet's progress on the chart. (If you are fortunate, you may even observe retrograde motion.)



Activity 6.1 Building an Astrolabe

The astrolabe is a simple device for measuring the altitude of an object. You can make one from a protractor and sighting-tube as shown in Figure 6.24. The washer on the thread marks the vertical direction so that when the sighting-tube is aligned with a star or planet, you can read the altitude of the object directly from the protractor.

Do not look through the sighting-tube at the sun. This can cause permanent eye damage in a very short time.

To use the astrolabe for determining the sun's altitude, fit a mask over one end of the sighting-tube and project light through the tube onto a paper screen as shown in Experiment 6.2.

Figure 6.24

Activity 6.2 Time-Exposure Photograph of the Sky

You can see the daily motion of the stars more closely with a time-exposure photograph of a region of the sky. Try to pick a moonless, clear night and set up the camera as far away from stray light as possible.

Set the camera on a tripod. Aim it at Polaris so that the camera's field of view includes several stars in the polar region such as those in the Big Dipper. As soon as it is dark, begin a time-exposure photograph. Leave the shutter open for several minutes. (The time will depend on observing conditions.) If you want to calculate the rate of motion for the stars, time the exposure accurately. Be careful not to shift the camera's position even slightly during the exposure.

When the exposure is complete, examine the photograph and use it to describe apparent diurnal motion of all celestial objects.

Repeat the procedure for other portions of the sky if possible. For some shots, include the horizon for reference, and look for stars rising or setting during exposure.

Activity 6.3 Building a Celestial Globe*

The celestial globe is a model of the celestial sphere. It is a useful tool for mapping the heavens and studying motions of the sun, moon, planets, and stars.

One model can be made from a large round-bottomed flask with a stopper to fit.

Coordinate systems can be marked on the sphere with a grease pencil or a permanent felt marking pen. Another method is to use thin strips of coloured cellulose tape or masking tape. Three coordinate systems, the horizon, the equator, and the ecliptic are used in the text and experiments.

You can refer to these to find out how to develop a coordinate system on your globe similar to the one shown in Figure 6.25.

The horizon of the observer can be represented by filling the flask half-full of water coloured with ink. Stopper the flask and tilt the axis of the flask to the angle of your latitude from the horizontal. The part of the sphere below the water's surface is below the observer's horizon. Now, if you rotate the flask westward about its axis you can simulate the daily motions of the sky and see the rising and setting of stars. Pick out regions of the sky which are always above the horizon, never visible, and rising or setting. Use your globe to show the motion of the celestial sphere as seen by an observer at the poles or on the equator.

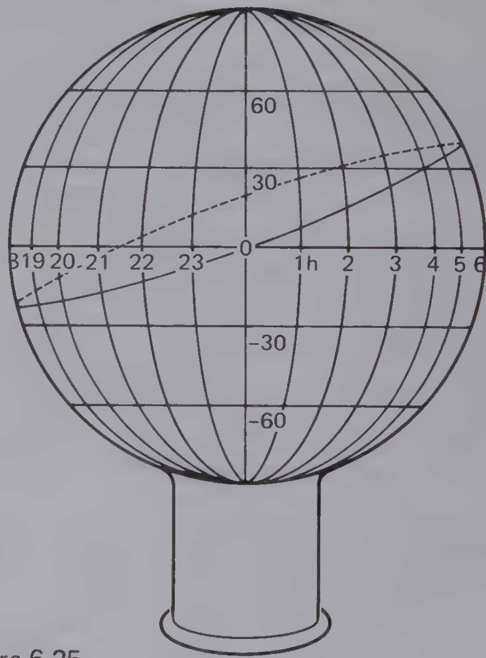


Figure 6.25

Activity 6.4 Celestial Globe Model 2

A second way to construct a celestial sphere is to use a large styrofoam ball with a diameter of approximately 15cm (6 inches).

Coordinate systems can be drawn on the sphere in the same way as outlined in the text and experiments. Use dark thread or a felt pen to mark circles on the globe.

Mark the position of stars with pins. Try to get them with coloured heads and use different colours for each constellation, or join stars in the same constellation with thread.

*A similar experiment appears in *You and Science,* by Paul F. Brandwein et al, copyright 1960 by Harcourt, Brace and World, Inc.

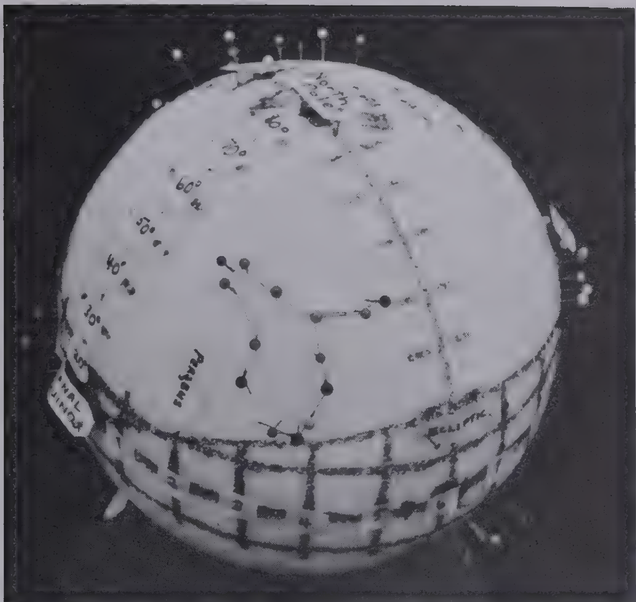


Figure 6.26

Activity 6.5 Sundial

The earliest sun clocks were gnomons (shadow casting rods) as used in Experiment 6.2. As the day wore on the gnomon's shadow behaved in a fairly predictable way, but since the sun's position changed with the seasons, the length of the hours changed too. At about the time of the Crusades, astronomers of the Islamic Empire realized that they could compensate for this seasonal change by pointing the gnomon at the North Celestial Pole. This would be at an angle above the horizontal equal to the observer's latitude.

If you are interested and can find a fairly permanent location, you can design and build your own sundial. It could be as simple as a stick driven into the ground. Calibrate a scale and use it to tell time. Try to estimate the uncertainty of your dial.

Figure 6.27

Some reference material can be found in the *Amateur Scientist* section of the August 1959 issue of *Scientific American*; the July 1972 issue of *Sky and Telescope*; and the book *Sundials* by Mayall and Mayall, published by Charles T. Brantford Co., Boston.

Activity 6.6 Observing Meteoroids

Meteoroids are small solid particles moving in orbits around the sun. They become visible only when they enter the earth's atmosphere at high speeds. (See Activity 2.5, Unit 1 for calculation of the speed of a meteoroid.) They can be seen any night of the year if you are far enough from light. At certain times of the year, however, they enter the earth's atmosphere in clusters and so the rate of observation increases. More meteors can be seen after midnight than before, and more during the last half of the year than during the first. Table 6.11 gives approximate dates for best viewing of Meteor Showers. It is based on several back issues of the *Observer's Handbook*. See a current issue of the *Observer's Handbook* for more up-to-date information.

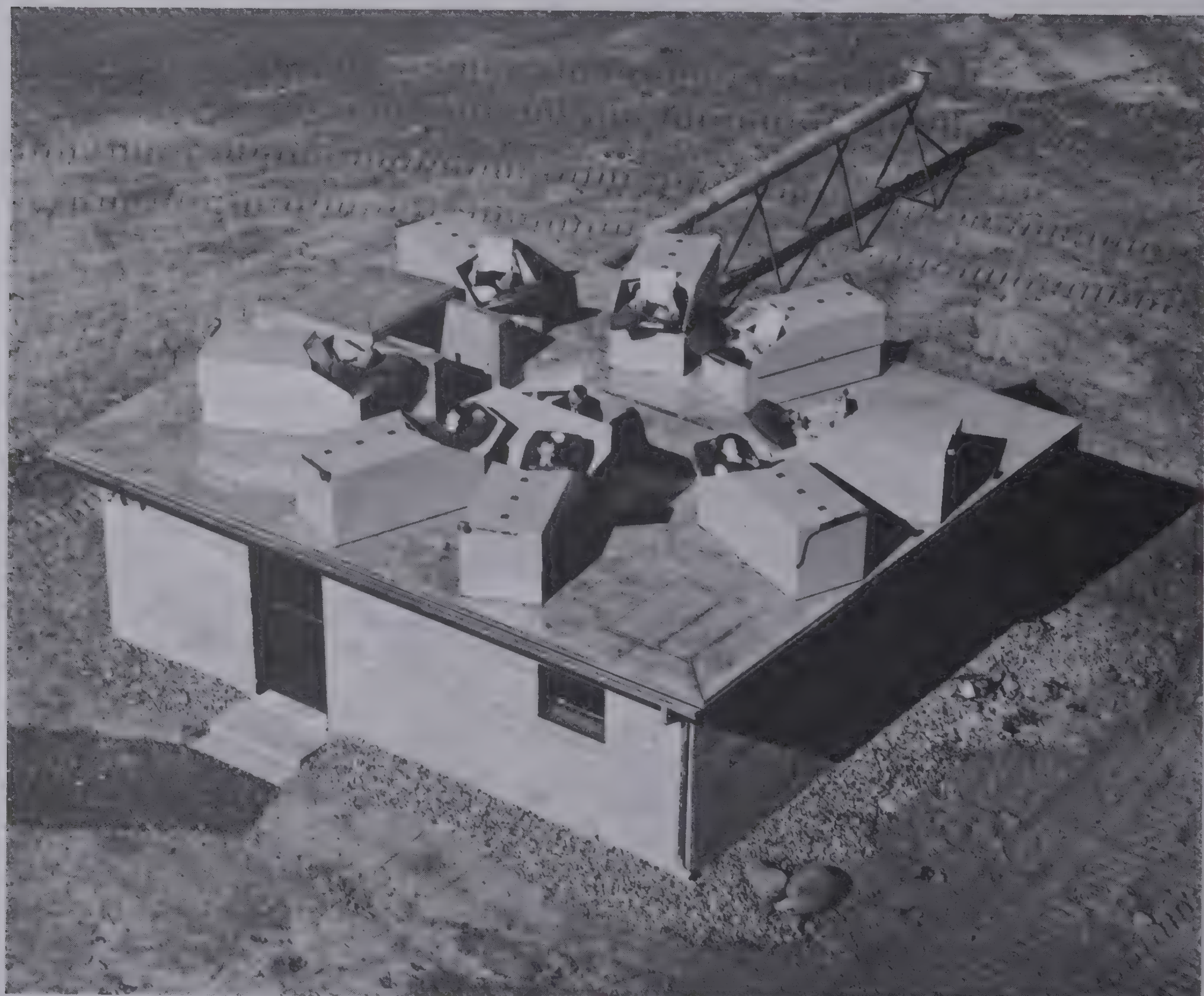
Two important items to note during observation are (a) the position among the stars from which the shower appears to radiate (the radiant), (b) the number of meteors seen per hour. Try to develop a theory to explain why more meteorites are seen after midnight than before midnight.

Figure 6.28 shows meterorite watchers in their "coffins" at the Springhill Meteorite Observatory near Ottawa.

Table 6.11
Meteor Showers (taken from *The Observer's Handbook)*

Shower	Shower maximum	Duration
Quadrantids	Jan. 3- 4	0.6 days
Lyrids	Apr. 21-22	2.3
Aquarids	May 4- 5	18
Aquarids	July 28-29	20
Perseids	Aug. 11-12	5.0
Orionids	Oct. 20-21	8
Taurids	Nov. 4- 5	30
Leonids	Nov. 16-17	4
Geminids	Dec. 13-14	6.0
Ursids	Dec. 22-23	2.2

Figure 6.28



Film Loop Notes

Film Strip 6.1 Retrograde Motion of Mars

This film strip consists of actual photographs taken of the night sky from the files of the *Harvard College Observatory* and shows the motions of Mars and Jupiter. In the first three sequences you will see Mars against the background stars for the following dates.

Jupiter also appears in Sequences 2 and 3.

In each sequence except the first, retrograde motion occurs for Mars and Jupiter. Also, during each sequence the planets are in opposition with the sun for the dates shown.

Table 6.12

Sequence	Duration	Dates of Opposition
1	August 3, 1941 to December 6, 1941	Mars: October 10, 1941
2	October 28, 1943 to February 19, 1944	Mars: December 5, 1943 Jupiter: January 11, 1943 and February 11, 1944
3	October 16, 1945 to February 23, 1946	Mars: January 14, 1946 Jupiter: April 13, 1946

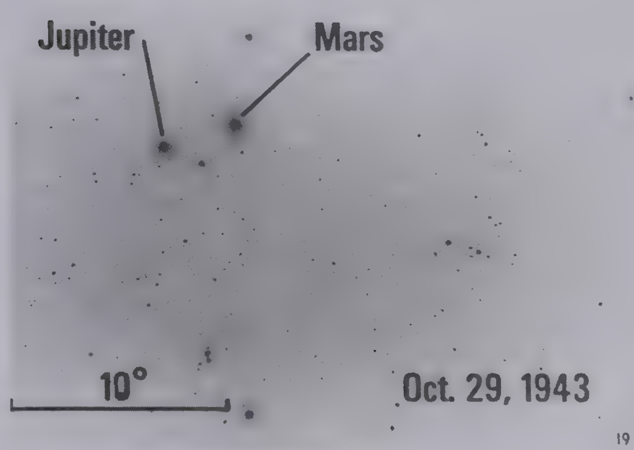
Q1 Why is an outer planet's motion retrograde when in opposition to the sun?

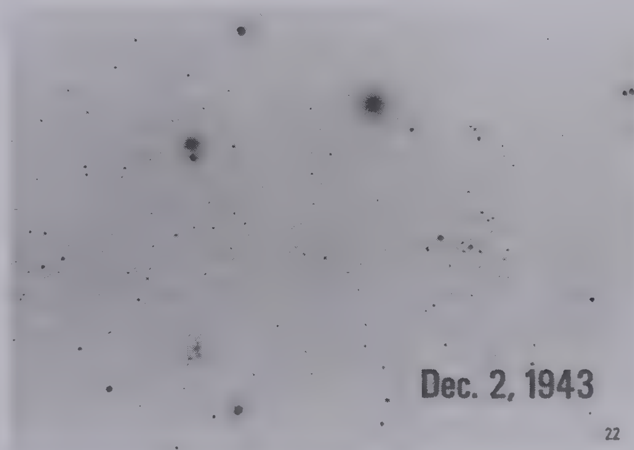
To use the strip, project it on a chalkboard or paper screen. For the first frame of each sequence mark the position of some brighter stars for reference. Also mark the position of the planet(s) and indicate the date. For each subsequent frame in the sequence, adjust the reference stars' positions to match the first frame and mark the planets' positions and the date. When the sequence is finished, draw a continuous curve through the points. (This should give you a plot similar to one in the last part of Experiment 6.5.)

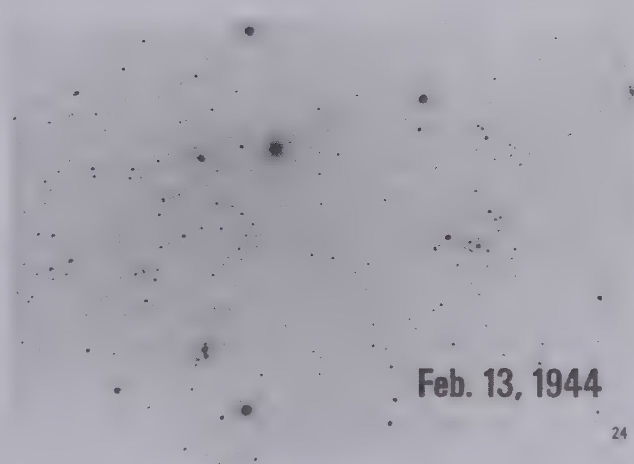
As a follow-up you can determine the duration of the retrograde motion in each case. Also, you can find the angular size of the retrograde loops by comparison with the scale of 10 degrees shown in one frame.

Q2 Why are the retrograde loops of Mars not always the same shape?

Q3 How do the retrograde motion of Mars and Jupiter compare?







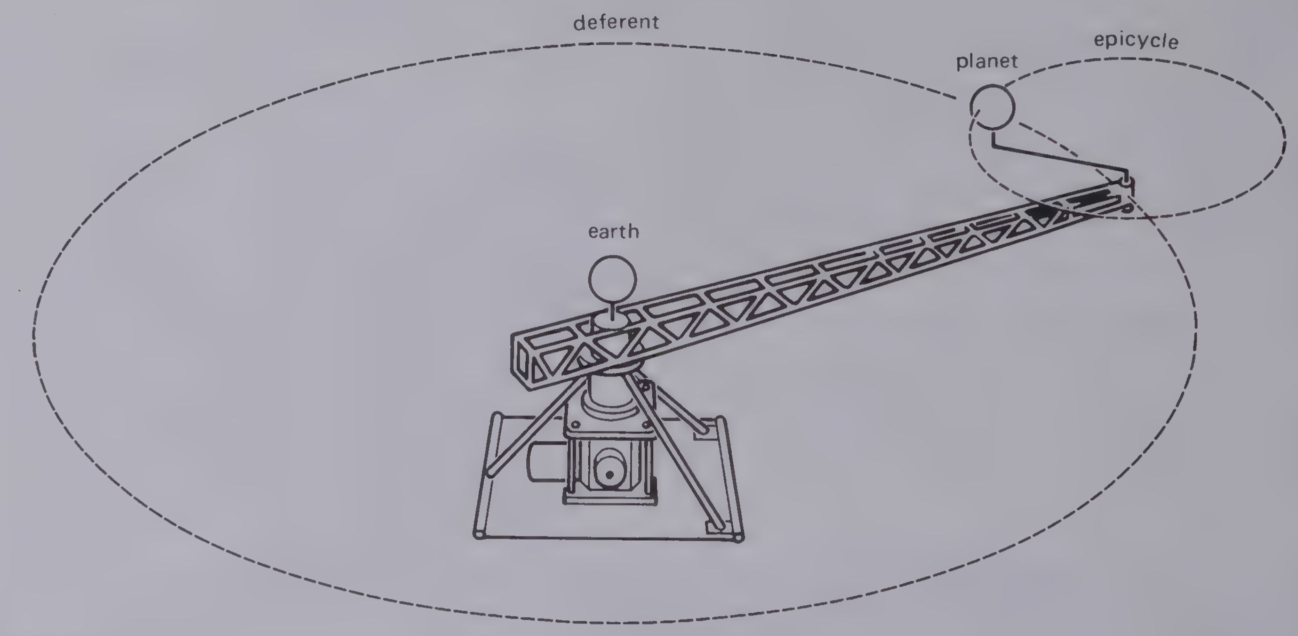


Figure 6.29

Film Loop 6.2 Retrograde Motion—Geocentric Model

This film loop presents a model of retrograde motion of a planet, as seen from the earth, based on Ptolemy's theory. To begin with, you see the simulation of a planet moving as if it were following an *epicycle* as it moved along the *deferent.* This is accomplished by an epicycle machine which appears when the studio lights come up.

Watch the first part of the loop to distinguish clearly between the deferent and epicycle.

Q1 What is the ratio of the period of the epicycle to that of the deferent shown in the loop.

The earth's globe on the centre of the machine is replaced with a camera fixed to point in one direction. Now you will see the planet as if you were an observer on a stationary earth always looking toward the same region or constellation in the sky during the planet's motion. The epicycle machine is turned on and part of the planet's path containing one retrograde motion is seen.

Q2 Does a planet's retrograde motion always occur at the same position in the sky?

Watch the planet's motion as it swings into view first moving east (to your left), then west (to your right), and then back again.

When the size of the bulb representing the planet, and the speeds, are decreased, the distance to the planet appears to be increased.

Q3 What change occurs for each of the following during retrograde motion as shown in the loop

(a) the planet's speed relative to the background stars?
(b) brightness of the planet?
(c) angular size of the planet?

Q4 How did the Ptolemaic Theory account for your observations in Q3? Discuss.

Chapter 7. Does the Earth Move?

In this chapter, experiments are based on observations of objects such as the sun and some of the planets, as seen from the earth. Analysis of these observations help us to understand the motions of these objects and to understand the question posed by the Copernican model, "does the earth move?"

Experiment 7.1 The Shape of the Earth's Orbit

As you move closer to or farther from some reference object, it appears to grow larger or smaller. If, however, you think of yourself as stationary during this motion, then you might well conclude that it is the reference object which is moving and not you.

In the first experiment of this chapter, you will examine a series of photographs of the sun's disc taken by the U.S. Naval Observatory at approximately one-month intervals during a year. Each of these photographs, taken when the sun was at a different direction from the earth (different longitude), shows the sun's disc having a slightly different diameter. You probably know that the earth orbits the sun. However, if you use the earth as a fixed frame of reference, based on photographic data the sun *appears* to orbit the earth at a varying distance. In fact, based on this evidence only, you would find it difficult to choose between the Copernican and Ptolemaic theories.

The purpose of this experiment is to plot the shape of the sun's apparent orbit as accurately as possible from the photographic data and to use the graph as a basis for obtaining the shape of the earth's orbit around the sun.

Procedure Measurement from the Film Strip

The sun photographs are on a film strip. Project the first frame on a chalkboard and adjust the projector so that the diameter of the sun's disc is approximately 50 cm. On each frame, the north-south axis of the sun is indicated with N and S. Measure the diameter of the sun's image, along the east-west direction, to the nearest millimetre. Repeat the measurement and record the average in a table similar to Table 7.1 which shows the dates and the sun's longitude for each frame.

Table 7.1

Date	Sun's longitude (degrees)	Diameter of projected sun's disc, d ( )	Relative distance earth to sun, r ( )
Mar. 21*	0		
Apr. 6	15		
May 6	45		
June 5	74		
July 5	102		
Aug. 5	132		
Sept. 4	162		
Oct. 4	191		
Nov. 3	220		
Dec. 4	250		
Jan. 4	283		
Feb. 4	315		
Mar. 7	346		
*vernal equinox			

FINDING THE RELATIVE DISTANCE FROM EARTH TO SUN

To draw the orbit you need the earth-sun distance to some convenient scale so that the orbit plot will not be too small or too large to fit on the paper. A convenient length to use for the earth-sun distance r for the date of the first frame is 10.0 cm. This will leave room for a plot of Mars' orbit on the same sheet. (See Experiment 8.2.) The value of r for other points along the orbit can be determined as follows.

As the distance r increases, the apparent diameter of the sun's disc d, which you have measured, from the film strip, will decrease in inverse proportion.

$$d \propto \frac{1}{r}, \text{ or } d \cdot r = \text{a constant.}$$

If we set the projector so that the first measurement of the sun's diameter $d_1 = 50.0$ cm, and we choose to make $r_1 = 10.0$ cm for the first point on the orbit, then

$$\begin{aligned} d_1 \cdot r_1 &= 50.0 \text{ cm} \times 10.0 \text{ cm} \\ &= 500 \text{ cm}^2 \end{aligned}$$

Since the product of d and r is a constant, for the second frame

$$d_2 \cdot r_2 = 500 \text{ cm}^2.$$

To get the value for r_2, rearrange the equation and substitute your measurement of d_2.

Then, $$r_2 = \frac{500}{d_2} \text{ cm.}$$

For example, if $d_2 = 51.2$ cm,

then, $$r_2 = \frac{500}{51.2} \text{ cm} = 9.80 \text{ cm.}$$

In the same way, calculate the relative earth-sun distance for each of the dates shown on the strip, and tabulate the results.

PLOTTING THE ORBIT

Use a piece of paper approximately 16" by 20" to plot the orbit. You may be able to obtain a single sheet of paper this size or you can make one by taping together four 8 1/2" x 11" sheets. You will need this large sheet so that you can plot a Mars orbit on the same paper outside the earth orbit when you do Experiment 8.2.

Place a point at the centre of the page to represent the earth. Draw the 0° reference axis which points in the direction of the sun's position on the vernal equinox to the right of your page. With a protractor measure the longitude angles for each of the other dates counterclockwise (eastward) from the 0° line and with a ruler draw lines radiating out from the earth at each of these angles as shown in Figure 7.1.

Along each of these lines measure off the relative distance to this point on the orbit for that date. Label each point with the date. Then draw a smooth curve through the orbit points using compasses or a French curve, to give you the shape of the orbit.

Q1 From your measurements in the experiment, is it possible to find the actual distance from the earth to the sun in your orbit? Discuss.
Q2 How do you think Ptolemy would have explained the apparent change in the sun's diameter?
Q3 Is your orbit circular? Discuss.
Q4 On your diagram, how far is the orbit's centre from the point representing the earth? (Express your answer in A.U.)

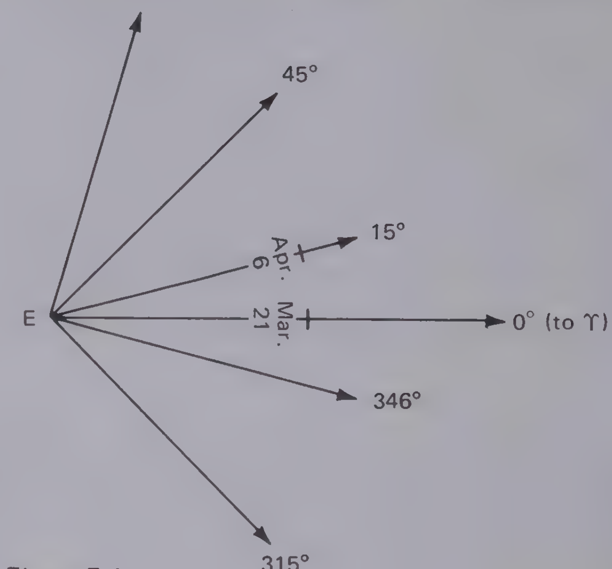


Figure 7.1

Q5 When is the sun closest to the earth, farthest from the earth?
Q6 For your location, can you explain the seasons in terms of the earth-sun distance? Discuss.

Locate the *apogee* (the point closest to the earth) and the *perigee* (the point farthest from the earth) on your orbit and draw a line joining them. This is the *major axis* of the orbit.

Measure the distances from the point representing the earth to the apogee and the perigee. (Express your answers in A.U.).

THE EARTH'S ORBIT

What you have plotted is the sun's orbit as it appears from a stationary earth. This corresponds to the geocentric Ptolemaic Theory. Copernicus suggested that things would appear the same if your frame of reference were shifted to a heliocentric universe. Therefore you should be able to use the same data to obtain the shape of the earth's orbit about the sun. The distances for each date would be the same but the directions would be different.

To see how the angles have to be changed, consider the earth-sun direction on March 21. On the vernal equinox the sun is between the earth and ♈. In the geocentric system this is our 0° reference as shown in Figure 7.2.

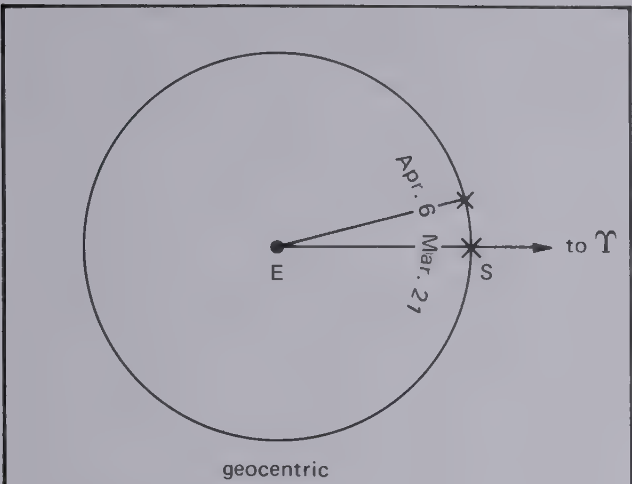


Figure 7.2

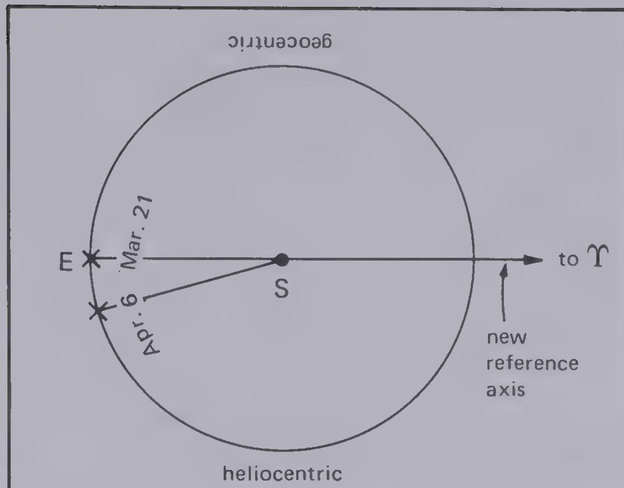


Figure 7.3

In a heliocentric system the earth would be 180° from the reference axis to ♈ as shown in Figure 7.3. The 0° reference axis is still the same and the sun is still between the earth and ♈ on March 21.

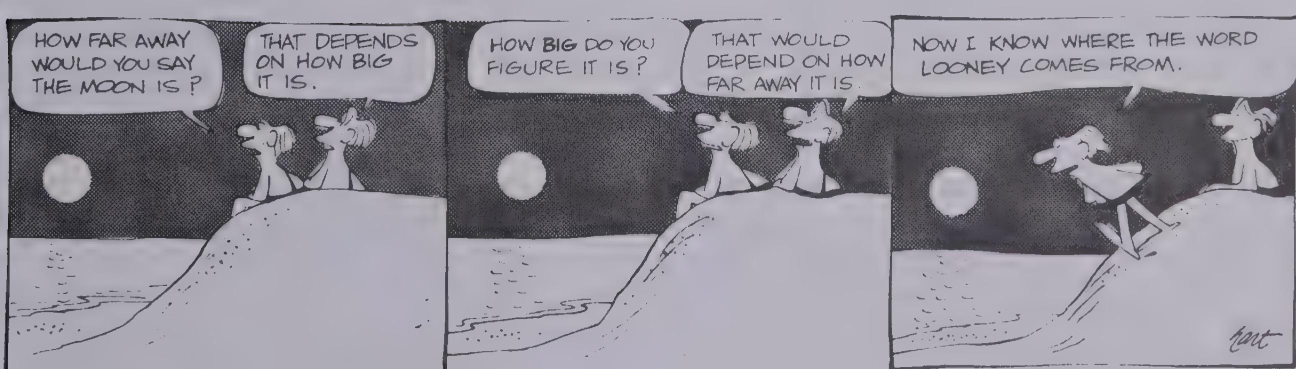
In the same way all of the other directions must be moved 180° counterclockwise to shift from a geocentric to heliocentric system. Do not replot the orbit.

The shift from geocentric to heliocentric can be achieved simply by rotating your initial plot through 180° and relabelling the reference direction so that it is still to your right, pointing toward the same point ♈ among the stars. Label the sun at the orbit centre. The dates along the curve will show the earth's position now instead of the sun's as shown in Figure 7.3.

Activities

"What if the Sun
Be Center of the World, and other Stars
By his attractive virtue and their own
Incited, dance about him various rounds?
Their wandering course now high, now low, then hid,
Progressive, retrograde, or standing still,
In six Thou seest, and what if seventh to these
The planet Earth, so stead fast though she seem,
Insensibly three different motions move? . . .

John Milton, *Paradise Lost*, Book VIII (1667)



Activity 7.1 Finding Orbit Radii

Copernicus treated planetary orbits as circles around the sun and calculated relative orbit radii from available data showing planetary positions. You can do the same calculation for Venus and Mercury as Copernicus did, using the following method.

Venus is an inner planet. If you watch its motion over a long period it appears to swing first east, then west of the sun to the same maximum angle or elongation, on either side of the sun. When Venus is at its maximum elongation, the line of sight from the earth to Venus will be a tangent to Venus' orbit. A radius drawn from Venus to the sun will form a right angle with the tangent as shown in Figure 7.4.

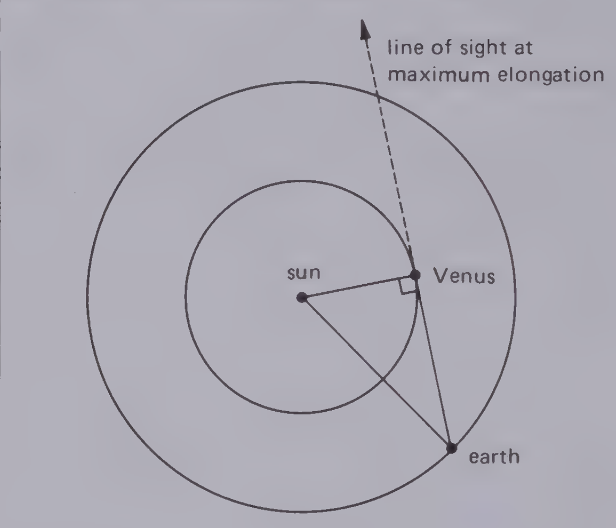


Figure 7.4

You can find the maximum elongation for Venus from Table 6.9 given in Experiment 6.5. This angle is the difference between the longitudes of Venus and of the sun, just as the planet begins or ends its retrograde motion. Maximum elongations for Venus are given in *The Observer's Handbook.*

Draw the right-angled triangle to scale and you can find the relative size of the orbit of Venus in terms of the earth's orbit radius. The radius of the earth's orbit is sometimes used as a standard unit of distance measurement in the solar system and is called an astronomical unit (A.U.). A modern value of 1 A.U. is 1.5×10^{11} metres. Another method is to "solve the triangle" using trigonometry.

In a similar way you can find the orbit radius for Mercury. The calculation for outer planets is more complicated, but Copernicus found their orbit radii in much the same way.

Table 7.2

Object	Orbit radius (A.U.)	Equatorial diameter (km)
Sun		1,400,000
Mercury	0.39	4,600
Venus	0.72	12,000
Earth	1.00	13,000
Mars	1.52	6,600
Jupiter	5.20	140,000
Saturn	9.54	120,000
Uranus	19.18	48,000
Neptune	30.06	45,000
Pluto	39.44	6,000

Activity 7.2 Scale Model for the Solar System

It is a real challenge to devise a scale model or drawing of the solar system. Most artist's conceptions are far out of scale. If you construct a simple scale model, it will give you a much better idea of the real, relative dimensions of the solar system.

Table 7.2 gives the orbit radii and diameters of the planets and the sun.

Use a styrofoam ball or tennis ball with a diameter of approximately 7 cm to represent the sun. With this scale, 1 cm is approximately equal to 200,000 km. The earth to sun distance of 1 A.U. = 1.5×10^8 km would be approximately 750 cm or 7.5 m for this scale. (You can measure the ball used to represent the sun in your model and calculate this dimension more accurately.) Work out other planetary distances and try to find appropriate objects to represent their diameters to scale. Join them with string at correct distances for as much of the solar system as possible.

Q1 Why not use a basketball to represent the sun in your model?
Q2 How large and how far from the earth would the moon be if included in the model?
Q3 The nearest star, *Alpha Centauri,* is approximately 2.7×10^5 A.U. from the solar system. How far away would this be for your model?

Activity 7.3 Frames of Reference

An interesting way to show that circular motion of an object around a stationary observer is equivalent to circular motion of the observer around the object is, with a camera, blinky, and turntable, to be set up as shown.

Take a time-exposure photograph first with the camera (observer) stationary and the blinky moving for one revolution in a circle on the turntable. Then switch positions of the camera and blinky and take a second time-exposure photograph of the blinky while the camera revolves once.

Compare the two photographs. Can you tell which was moving, the camera or blinky?

In observing the diurnal motions of the planets, sun, moon, or stars, is it possible to tell whether the earth is moving or stationary?

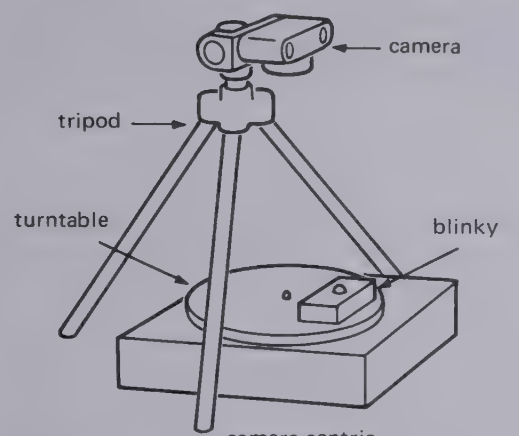


Figure 7.5

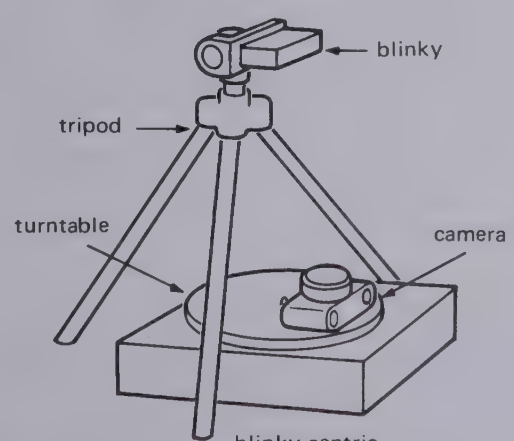


Figure 7.6

Figure 7.7

Activity 7.4 Foucault Pendulum

Jean Bernard Léon Foucault (1819-68) sought an experiment which would prove that the earth did indeed rotate. His experiment performed in the Panthéon, Paris in 1851 consisted of suspending a cannonball from a 60-metre wire. He set it swinging and waited and watched. Foucault expected that if the earth were rotating, it would do so under the pendulum without disturbing its plane of swing which would remain fixed relative to the stars. As a result, the pendulum's plane of swing would appear to swing in a direction opposite to the earth's rotation.

You can try this experiment although it is a delicate and difficult one to perform. You will need an area with a high ceiling such as a large stairwell or a gymnasium where there is very little traffic. Cannonballs are hard to come by these days but you could use an inertia ball or a shotput. Inertia balls usually have a hook attached. One way to suspend the shotput is to put it in a large juice can and hang the can at the end of the pendulum. The longer the pendulum, the better. It must be suspended so that it is free to swing in all directions. One method that works well is shown in Figure 7.7. Take a hook, and attach one end

to the pendulum wire. Use a metal punch and a hammer to make a "ding" in the edge of a basketball net hoop or a piece of metal which can be clamped up high. Bend the hook and place the end of it in the "ding".

You want the pendulum to have a flat swing with a fairly small amplitude. To launch it so that it is not pushed to the side, which would make its swing elliptical, pull it back with a string and attach it to a chair. When you are ready to begin, burn the string close to the pendulum wire. Mark its initial plane of swing on the floor. Then wait and watch for evidence of the earth's rotation.

The pendulum should rotate once in 24 hours at the poles. As the site of the experiment is moved toward the equator, the rate of rotation decreases.

Q1 How often would the pendulum rotate in a day if placed at the equator?

MODEL OF A FOUCAULT PENDULUM

The principle of the Foucault pendulum experiment can be shown with a model suspended on a turntable as shown in Figure 7.8.

Figure 7.8

Film Loop Notes

Film Loop 7.1 Retrograde Motion—Heliocentric Model

In this loop, the epicycle machine has been assembled to give a heliocentric model of two planets—earth (represented by a light blue globe) and an outer planet which could be Mars (white globe) orbiting the sun (yellow globe). Their orbits are concentric circles.

In the first part you see the two planets from above the plane of motion. The earth orbit period is 1 year with the machine set to give the outer planet the same orbit period as Mars, 687 days.

The earth is then replaced with a camera which points in the same direction relative to the stars at all times. This direction is shown by an illuminated arrow.

Retrograde motion occurs when Mars is in opposition, meaning that the earth is moving between Mars and the sun. The retrograde motion for this model appears much the same as for the geocentric model with the planet first moving eastward to opposition, then reversing its direction, looping, and then going eastward again.

The time between successive oppositions (the phase period) is 2.1 years as shown on the loop. However, every retrograde motion cannot be seen by the camera because of its limited field of view. As seen from the earth during the third opposition on the loop, the sun first moves across the field of view in its yearly motion followed by Mars which traces a retrograde motion loop. This is followed by the sun again moving across the same portion of the sky.

Q1 What changes occur in the following during Mars' retrograde motion
(a) earth-Mars distance?
(b) apparent size of Mars?
(c) apparent brightness of Mars?
Q2 Are these changes predicted qualitatively by the Copernican heliocentric model? Discuss.
Q3 Why is the phase period for Mars, 2.1 years, even though the period of Mars' orbit is 687 days (less than two years)?

Chapter 8. A New Universe Appears

Kepler, Tycho, and Galileo opened the eyes of astronomers with new insights and observations. In this chapter, the experiments and activities demonstrate the kinds of discoveries made by these men and others.

Experiment 8.1 The Ellipse

The purpose of this laboratory exercise is to acquaint you with the important characteristics of the ellipse and to give you practice drawing them. It is followed by some calculations for various ellipses and planetary orbits.

The ellipse is important in astronomy because it describes fairly accurately the shape of planetary orbits. Kepler first used the elliptical shape in this way, as he tried to solve the problem of Mars' orbit.

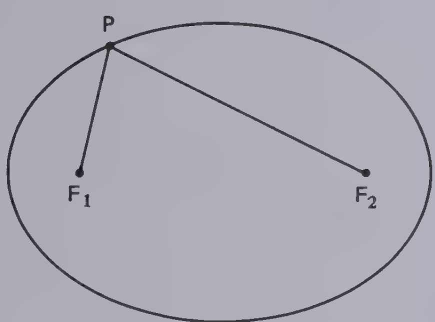


Figure 8.1

The ellipse is defined as the path traced out by a point which moves so the sum of the distances between it and two other fixed points (foci F_1 and F_2) remains constant. In the diagram,

$$|PF_1| + |PF_2| = \text{a constant}.$$

To find the constant, move P around to either end of the ellipse, and you can see that $|PF_1| + |PF_2|$ equals the length of a line drawn through the two foci and extended to meet the ellipse. This line is called the *major axis* and is usually represented by $2a$. Therefore our definition can be written

$$|PF_1| + |PF_2| = 2a.$$

The distance between the foci is represented by $2c$. The average radius R of the ellipse is half the major axis or a.

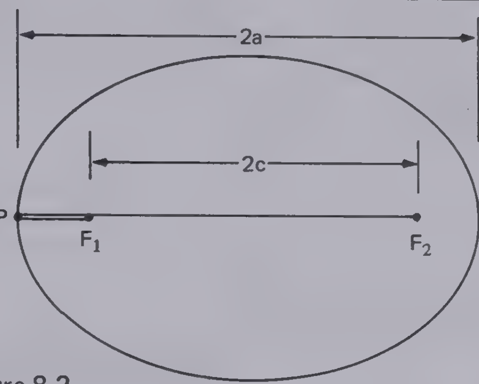


Figure 8.2

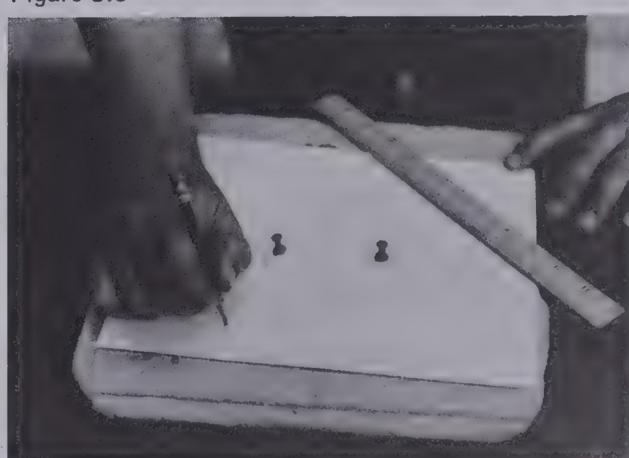
Procedure Drawing the Ellipse

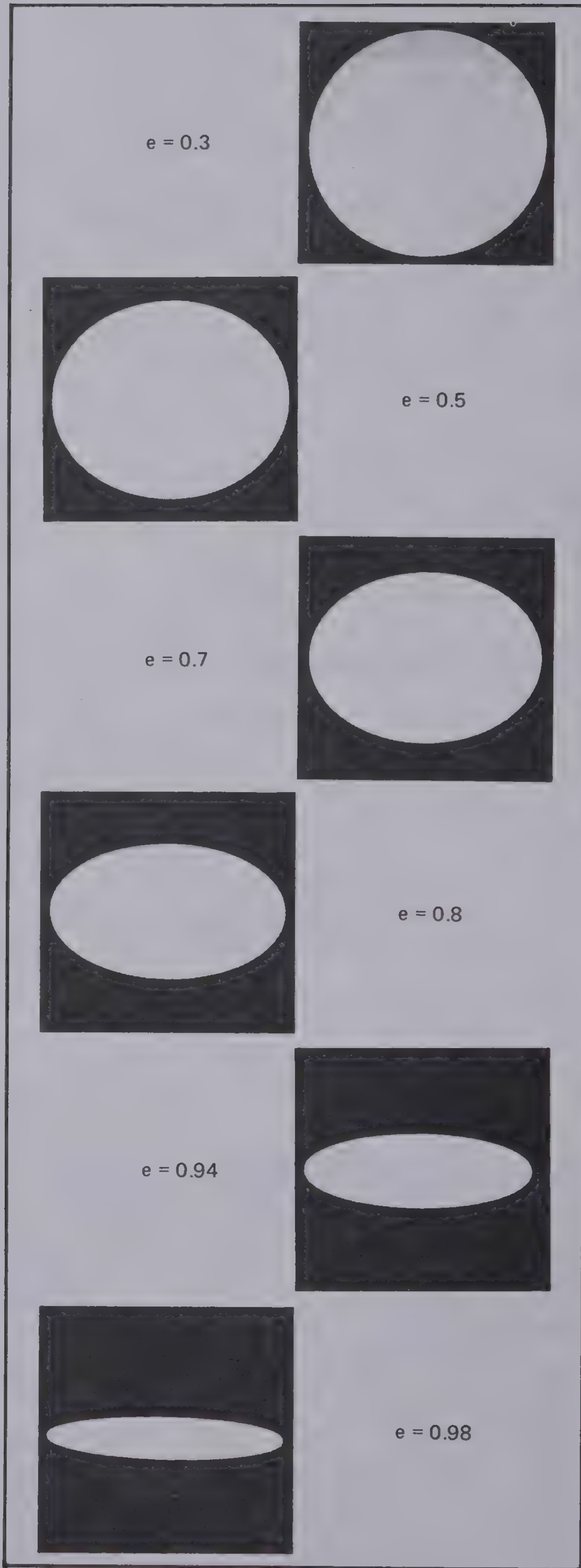
A simple method of drawing an ellipse is based on its definition. Obtain a piece of tackboard, two thumbtacks, a piece of thread. Place the two tacks where you want your foci, attach one end of the thread to each tack and adjust its length to equal the length of major axis you want; slip the pencil point in the loop and swing it around keeping the thread taut and the pencil vertical. This will give you an ellipse.

Draw ellipses with the following characteristics:

(a) major axis = 15 cm.
distance between foci = 5 cm.

Figure 8.3





(b) $2a = 15$ cm, $2c = 10$ cm.
(c) $a = 7.5$ cm, $c = 2$ cm.
Compare the shapes of these ellipses.

ECCENTRICITY

To describe the shape of an ellipse you can use a quantity called the ellipse's eccentricity. The eccentricity represented by e is defined

$$e = \frac{c}{a} \text{ or } e = \frac{c}{R}.$$

Calculate the eccentricity for each ellipse which you have drawn.

Q1 (a) What is the eccentricity of a circle?
(b) How could you draw a circle with the thread and tacks?
Q2 What is the maximum possible eccentricity for an ellipse?
Q3 How is the eccentricity of an ellipse related to its shape?

PLANETARY ORBITS

According to Kepler's *Law of Ellipses,* every planet in the solar system orbits in an ellipse with the sun at one focus. The other focus is empty. The nearest point on the orbit to the sun is called the *perihelion* and the distance from perihelion to the sun is represented by *Rp.* Similarly the farthest point on the orbit from the sun is called the *aphelion.* The distance from it to the sun is represented by *Ra.*

The parameters of the ellipse already discussed can be expressed in terms of *Ra* and *Rp.*

Major axis $2a = Ra + Rp,$
Distance between the foci $2c = Ra - Rp,$
Eccentricity $e = \frac{Ra - Rp}{Ra + Rp}.$

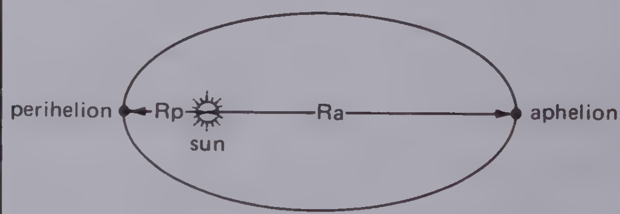


Figure 8.4

Check these relationships for yourself.

Q4 The perihelion distance of the earth in its orbit is 0.983 A.U. The average radius of the earth's orbit is 1.000 A.U. Find the eccentricity of the earth's orbit. Compare these values with what you have found for your earth orbit in Experiment 7.1.

Q5 The eccentricity of Pluto's orbit is 0.249—the largest of any planet in the solar system. The average radius of the orbit is 39.5 A.U.

(a) Draw a scale diagram of Pluto's orbit.

(b) Find the aphelion and perihelion distances in A.U. for Pluto from your diagram.

Q6 The eccentricity of the orbit of Halley's comet is 0.967 and its perihelion distance is 0.59 A.U.

(a) Calculate its aphelion distance.

(b) Find the major axis of the Halley's comet orbit.

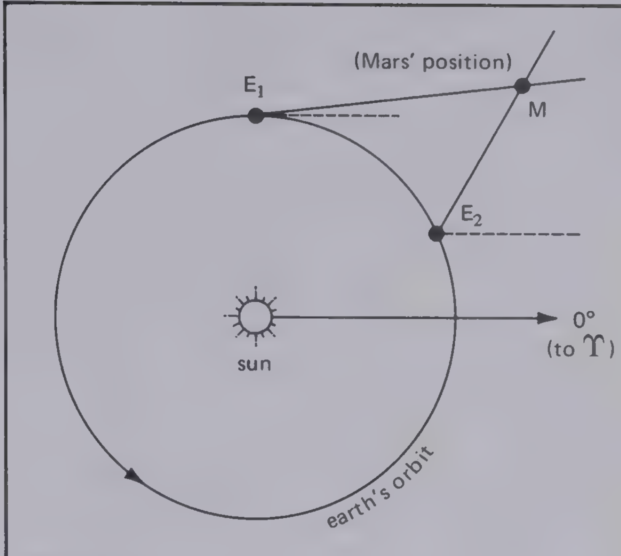


Figure 8.5

Experiment 8.2 Mars' Orbit

This experiment is based on the method used by Johannes Kepler in plotting the orbit of Mars. Kepler relied on planetary data which had been entrusted to him by Tycho Brahe, when the old astronomer lay dying.

Instead of using Tycho's data, you will obtain your own from star photographs showing Mars against the background stars at various dates between 1931 and 1950. These were taken with the small camera of the Harvard Sky Patrol. We shall assume that the background stars remained fixed during this period of observation.

KEPLER'S METHOD

Kepler used Tycho's planetary data to plot the earth's orbit first, and from that he proceeded to plot the orbit of Mars. (See page 33 in text.) In our experiment we shall use the earth orbit already found in Experiment 7.1, and we shall build the Mars orbit on it in the same way as Kepler did.

To find a single point in Mars' orbit, Kepler took Tycho's record of Mars' position against the background stars as seen from the earth, at some position of E_1 shown by the direction line in Figure 8.5.

Then he turned through the pages of Tycho's record to a date exactly one Martian year (687 days) later when he knew that Mars would be in the same place in its orbit. From the earth, which was now at a different point E_2 in its orbit, Mars appeared to have a different position or direction. The intersection of the two direction lines, E_1M and E_2M, located one point on Mars' orbit. Kepler found 40 points in this way.

Procedure

COORDINATES OF MARS

The booklet contains 16 photographs showing Mars among the stars. The photographs are paired *A* and *B*, *C* and *D*, . . . *O* and *P* to show Mars at intervals of exactly one Martian year. These dates are listed in Table 8.1. Overlays have been prepared for each photograph showing a portion of the ecliptic marked off in degrees longitude. Perpendicular to the ecliptic are axes calibrated in degrees latitude. (See Experiment 6.5 for a review of the Ecliptic Coordinate System.) Also, on each overlay are circles corresponding to positions of the brightest stars and to Mars, which is about the brightest object in the photograph.

To find the coordinates of Mars, align the overlay so that it matches the stars in the photograph, then read off the longitude and latitude of Mars. (Only the longitudes are necessary for finding the shape and size of Mars' orbit. You will need the latitudes only if you wish to study the inclination of Mars' orbit in Experiment 8.4.) Try to do this as accurately as possible (at least to the nearest 0.5 degree) because

Table 8.1
Positions of Mars

Photograph	Date	Position of Mars	
		Longitude	Latitude
A B	Mar. 21, 1931 Feb. 5, 1933		
C D	Apr. 20, 1933 Mar. 8, 1935		
E F	May 26, 1935 Apr. 12, 1937		
G H	Sept. 16, 1939 Aug. 4, 1941		
I J	Nov. 22, 1941 Oct. 11, 1943		
K L	Jan. 21, 1944 Dec. 9, 1945		
M N	Mar. 19, 1946 Feb. 3, 1948		
O P	Apr. 4, 1948 Feb. 21, 1950		

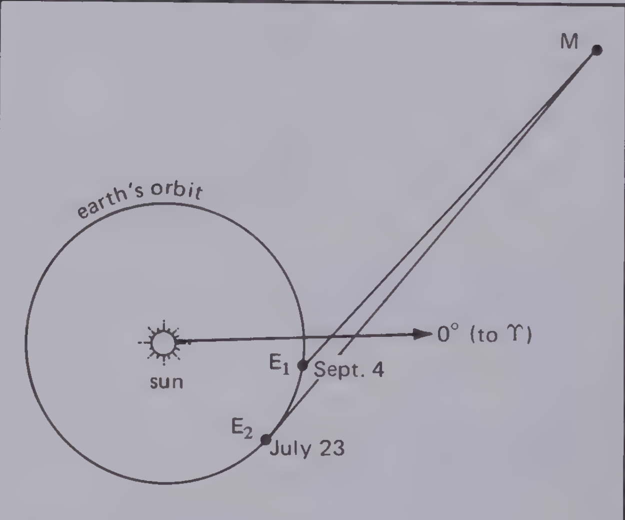


Figure 8.6

the entire experiment depends upon these results. Tabulate your data.

If the booklets and overlaps are not available, you can obtain the same type of data from a list of planetary longitudes such as the one in Table 6.9 in Experiment 6.5. It will be necessary to interpolate between the 10-day intervals to find dates 687 days apart. Also, with the limited number of years shown in the table, some of the pairs of data, for example, Sept. 4, 1973 and July 23, 1975, give longitude direction lines which cross the earth's orbit to form a long skinny triangle as shown in Figure. 8.6. The accuracy of this construction is not good as a small error in either angle measurement moves the intersection point on the Mars orbit by a large amount.

PLOTTING MARS' ORBIT

Use the earth orbit which you obtained in Experiment 7.1 as the basis for your plotting. If that plot is not available, you can approximate it by drawing a circle having a radius of 10.0 cm in the centre of a 16″ X 20″ sheet of paper which can be made by joining four 8 1/2″ X 11″ sheets with tape. Graph paper is best. Be certain that your earth orbit has the sun at the centre and the direction of the vernal equinox to the right as shown in Figure 8.7.

Locate the earth's position on its orbit for each of the dates in Table 8.1. To do this, remember that the earth revolves 360 degrees counterclockwise in 365

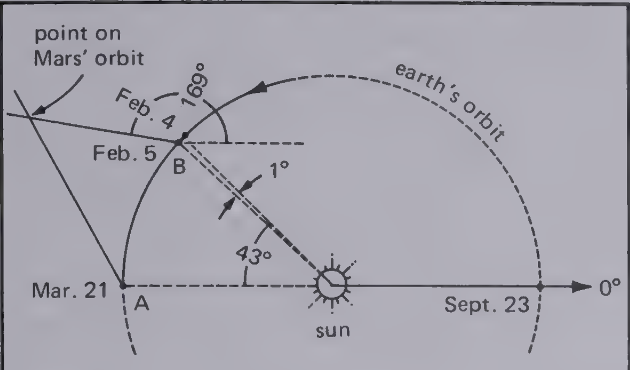


Figure 8.7

days, or approximately 1 degree per day in its orbit. Work either from earth-position dates in Experiment 7.1, or from the equinoxes. For example, photograph *A* is dated March 21 which is the vernal equinox position. Photograph *B* is dated February 5, 1933 which is 43 days before or 43 degrees clockwise from the vernal equinox. It can also be found 1 degree counterclockwise from February 4, one of the earth orbit dates.

At each point, *A, B, C,* etc. draw a reference line parallel to the 0 degree line. Measure the observed longitude angle counterclockwise from the reference line. Intersections of lines from each point of photographs give 8 points on Mars' orbit.

Join the orbit points with a smooth curve. Use the idea of symmetry to help you obtain the section of the orbit where the intersection points are very far apart. If you did Experiment 8.1, try the technique shown there to see if the orbit is an ellipse.

Q1 What is the shape of the orbit?
Q2 Where is the sun in relation to the orbit?

You will now have a good approximation of Mars' orbit, to scale, shown relative to the earth's orbit. You can stop here or go on to do the following parts of the experiment depending on your interest or the time available.

CHARACTERISTICS OF THE ORBIT

Find and label the points on the orbit nearest the sun (perihelion) and farthest from the sun (aphelion). They should be on opposite sides of the sun.

Draw the major axis of the orbit. This should pass through the aphelion and the perihelion points and through the sun's position.

Q3 What is the average radius (one-half the length of the major axis) of Mars' orbit? Express your answer in A.U.
Q4 What is the longitude of Mars' perihelion as seen from the sun?
Q5 What is the distance in A.U. of Mars' closest approach to the earth?
Q6 How far is the sun from the centre of the major axis? Express your answer in A.U.
Q7 Calculate the eccentricity of Mars' orbit using one of the formulas shown in Experiment 8.1.

The accepted values of the following characteristics for Mars' orbit are:

eccentricity, $e = 0.093$
average radius, $R = 1.52$ A.U.
longitude of perihelion $= 335°$.

Find the percentage error in your results.

TESTING KEPLER'S LAWS

Q8 Is the shape of the orbit similar to the shape predicted by Kepler's Laws? Discuss.

Does the orbit agree with Kepler's *Law of Areas*? To find out, draw lines from the sun to at least two pairs of points showing Mars' position on the orbit. This will give you the sectors of the ellipse as shown in Figure 8.8.


Figure 8.8

Find the area in each sector you choose. You can do this by counting squares if you have used graph paper. Another method is to measure the area in grams. To do this, trace each sector on another piece of paper and cut out each sector's shape. Weigh the pieces of paper to find the relative areas. A third way is to approximate each sector with a triangle and find its area using the formula: Area = 1/2 X base X height.

Table 8.2

Dates	Area of sector ( )	Elapsed time (days)	Area per day ( )

Find the number of days between each pair of points and record results in a table similar to Table 8.2. Calculate the area per day swept out by Mars in each sector. Repeat for the other sectors if you have time.

Q9 Do your results satisfy Kepler's Law within experimental error?

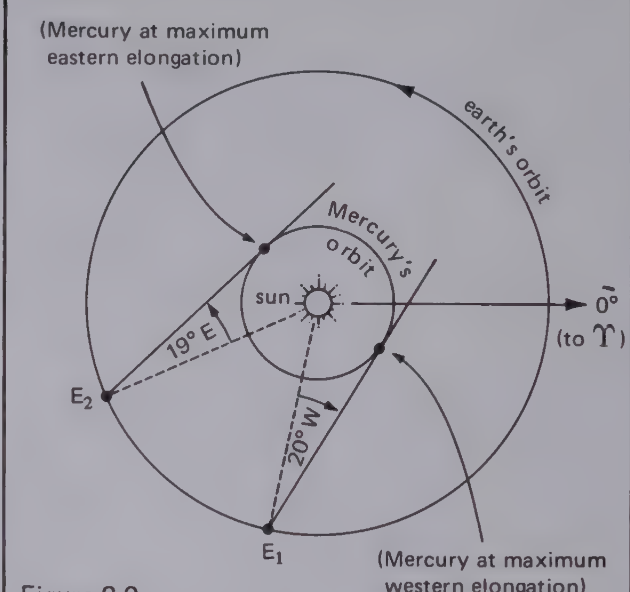


Figure 8.9

Experiment 8.3 Orbit of Mercury

Mercury is an exceptional planet. It is nearer the sun and travels faster in its orbit than any of the other planets. Also, the eccentricity of its orbit is greater than that of any other planet except Pluto.

As seen from the earth, this inner planet seems to travel quickly from one side of the sun to the other, several times each year. Its maximum elongation, which is its angular distance either east or west of the earth-sun line, varies between 18° and 28°. When Mercury reaches maximum elongation, the sight-line from earth to Mercury is tangent to Mercury's orbit as shown in Fig. 8.9.

In this experiment use the maximum elongations of Mercury shown in Table 8.3 (or find them in *The Observer's Handbook* for this year) to obtain the orbit of Mercury.

Procedure Plotting the Orbit

Since the tabulated elongations are taken as seen from the earth, you will work from a diagram of the earth's orbit. You can use the earth orbit which you obtained in Experiment 7.1 as the basis for your plotting. If that plot is not available, you can approximate it with a circle of radius 10.0 cm in the centre of 8 1/2" X 11" piece of paper. Be certain that this orbit has the sun at the centre and the direction of the vernal equinox to the right as shown in Figure 8.9.

Locate the earth's position on its orbit for each of the dates in Table 8.1 as explained in Experiment 8.2. From each point, draw a radius from the earth to the sun.

Measure the maximum elongation angles from the earth-sun line for each date. Remember, *eastern elongations are measured counterclockwise* (to the

Table 8.3
Maximum Elongations of Mercury during 1972
(taken from *The Observer's Handbook)*

Elong. east — evening sky		Elong. west — morning sky	
Date	Elong.	Date	Elong.
Mar. 14	18°	Jan. 1	23°
July 10	26°	Apr. 28	27°
Nov. 5	23°	Aug. 25	18°
		Dec. 14	21°

left of the sun) and *western elongations are measured clockwise* (to the right of the sun). Then, draw sight-lines from the earth for each elongation.

To find the point where Mercury is along each sight-line, you can use the fact that a line, drawn from the sun to Mercury's position at maximum elongation, will form a right angle as shown in Figure 8.10. This is the closest point to the sun along the sight-line.

Draw in the orbit as accurately as possible with a curve through each of the points. Since each sight-line is tangential, the orbit should never cross a sight-line.

Q1 What is the shape of the orbit?
Q2 As seen from the earth, would Mercury show phases as it orbits? Discuss using diagrams.

You have obtained the Mercury orbit which was the aim of the experiment. If you have time, you can study the characteristics of the orbit in more detail.

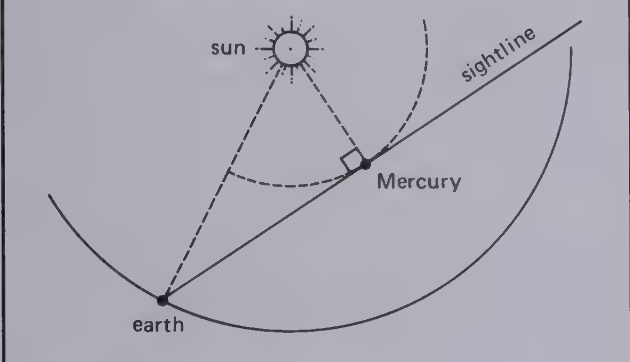


Figure 8.10

CHARACTERISTICS OF THE MERCURY ORBIT

Find and label the aphelion and perihelion points on the orbit. Draw the major axis of the orbit through these points and through the sun.

Q3 What is the average radius R of the Mercury orbit? Express your answer in A.U.
Q4 What is the longitude of Mercury's perihelion as seen from the sun?
Q5 What are the perihelion and aphelion distances in A.U. for the orbit?
Q6 Calculate the eccentricity of the orbit using one of the formulas shown in Experiment 8.1.
Q7 How far in A.U. is the sun from the centre of the Mercury orbit?
Q8 What is the average number of degrees per day that Mercury moves in its orbit (a) at perihelion? (b) at aphelion?

The accepted values of the following variables for the orbit of Mercury are:

eccentricity,	$e = 0.207$
average radius,	$R = 0.387$ A.U.
longitude of perihelion	$= 77°$.

Find the percentage error in your results.

TESTING KEPLER'S LAWS

To test the *Law of Elliptical Orbits* locate the foci of the orbit of Mercury. Use a thread adjusted to the corrected length ($2R$) and tacks, to draw an ellipse as you did in Experiment 8.1. Compare the orbit and ellipse.

Test the *Law of Areas* in the same way as that described in Experiment 8.2. Find the percentage error in your results.

OBSERVING MERCURY

During eastern elongation Mercury can be seen as an evening star setting shortly after the sun. During western elongation, Mercury is a morning star, rising a little before the sun. It is visible to the naked eye during each elongation, but the best times for viewing are in the spring as an evening star, and in the fall as a morning star. Sometimes Venus, which is much brighter and easier to see, is near Mercury which is much dimmer. In this case, you can use Venus to locate Mercury. (Consult the *Observer's Handbook* for the most favourable elongations.)

Experiment 8.4 Inclination of Mars' Orbit

In Experiment 8.2 you obtained observations of the longitude and latitude of Mars at various points in its orbit. The changing latitude indicated that Mars was not moving along the ecliptic but was sometimes above and sometimes below it. You used the longitudes to obtain the orbit shape and ignored the latitudes in that experiment. In this experiment you will use the observations of latitude to study another characteristic of Mars' orbit.

Two orbits in the solar system can be represented by ellipses drawn on two pieces of cardboard or on file

cards, each one corresponding to an orbit plane of a planet or comet. The sun is at one focus of each ellipse. To show the orbits in three dimensions, the cards can be cut and slipped together as shown in Figure 8.11.

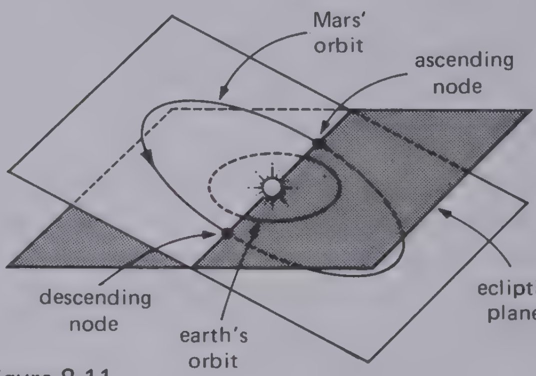


Figure 8.11

If one card represents the ecliptic plane containing the earth's orbit, the other card may show the orbit of a planet such as Mars moving above and below the ecliptic plane. The points where Mars' orbit intersects the ecliptic plane are called the *ascending* and *descending nodes* depending on whether the planet is moving northward or southward as it crosses the ecliptic plane. The tilt or inclination of this second plane will determine the variation in the planet's latitude and vice versa. In this experiment you can use the values of Mars' latitudes from Experiment 8.2 to find the inclination of Mars' orbit.

The latitudes in Experiment 8.2 have been measured as seen from the earth (geocentric latitudes θ_g). Since the sun is at a focus of the orbit, to find the inclination of the orbit, you will need to calculate the heliocentric latitude θ_h of Mars. The relationship between θ_h and θ_g is developed in the following theory block and is

$$\theta_h = \frac{r_{EM}}{r_{SM}} = \theta_g,$$

where r_{EM} = distance from Mars to earth,

r_{SM} = distance from Mars to the sun.

For example, if on a particular date

$$r_{SM} = 12 \text{ cm}$$

(1.2 A.U. for a scale of 10 cm: 1 A.U.),

$$r_{EM} = 6 \text{ cm (0.6 A.U.)}$$

and $\theta_g = 4.0°$,

then $\theta_h = \frac{0.6}{1.2} \times 4.0$

$= 2.0°$.

Measurements

First measure and tabulate the distances r_{EM} and r_{SM} from your orbit points for each photo or graph as shown in Figure 8.12. Be careful to get the correct position of the earth for each date.

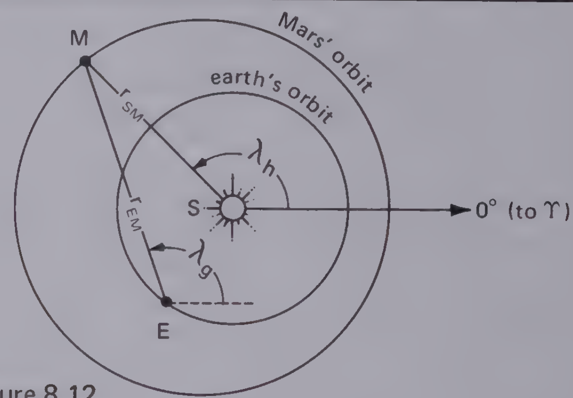


Figure 8.12

Calculate the heliocentric latitudes using the formula above.

Tabulate your results.

Next, for each position of Mars measure the heliocentric longitude λ_h, the angle counterclockwise from the zero-degree line pointing to ♈ and the Mars-sun line as shown in Figure 8.12. (One measurement will do for each pair of dates *AB*, *CD*, . . .) Tabulate your results.

Analysis

Plot a graph of heliocentric latitude versus heliocentric longitude for Mars. Your graph should look something like Figure 8.13.

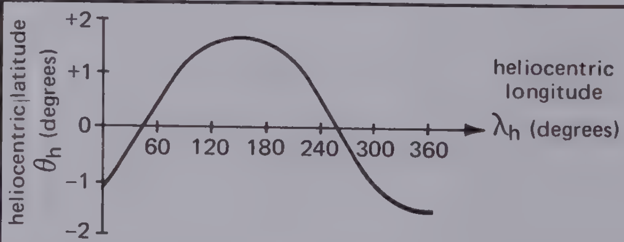


Figure 8.13

Conversion From Geocentric to Heliocentric Latitude

Most astronomical observations are geocentric. It is sometimes simpler to work with heliocentric data, in particular when dealing with planetary orbits, in this chapter. Therefore we must be able to convert from geocentric to heliocentric coordinates. For example, Mars' orbit is tilted with respect to the ecliptic plane so that its geocentric latitude changes as Mars orbits the sun.

In Experiment 8.2 you ignored the latitudes in your plotting and showed the Mars orbit as if it were in the ecliptic plane. In Figure 8.14, M represents Mars' actual position in space and M' represents the projection of this point on the ecliptic plane; θ_g and θ_h give the angle of M above the ecliptic plane as seen from the earth and sun respectively.

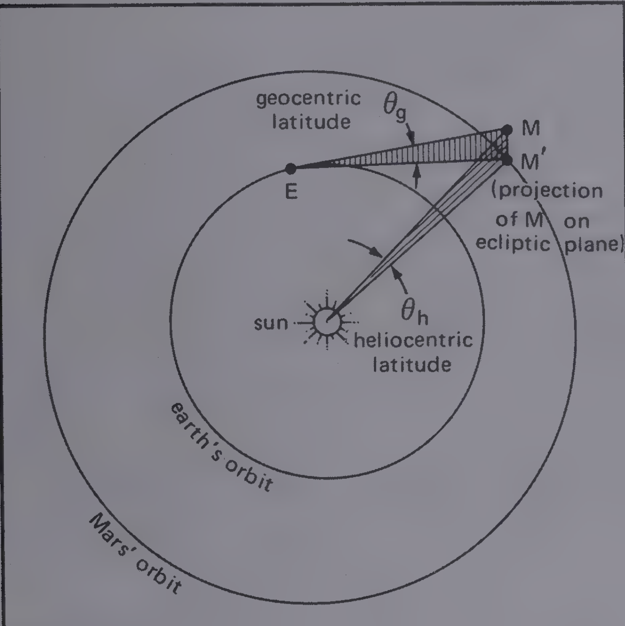


Figure 8.14

As shown, the angle of Mars above or below the ecliptic at any instant as seen from the earth (geocentric latitude θ_g), will usually not be the same as the one seen from the sun (heliocentric latitude θ_h). However, the distance of Mars from the ecliptic plane MM' will be the same. Two right-angled triangles are formed, $\Delta\ S\ M\ M'$ and $\Delta\ E\ M\ M'$, which can be superimposed as shown in Figure 8.15. Their vertex-angles represent θ_h and θ_g respectively.

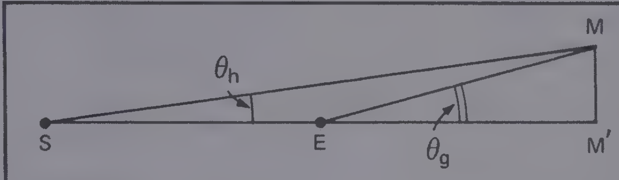


Figure 8.15

For *small* angles (less than 5 degrees) the following ratios are very close to being exact.

$$\frac{MM'}{SM'} = \theta_h \times \text{a constant.}$$

$$\frac{MM'}{EM'} = \theta_g \times \text{a constant.}$$

Dividing the ratios,

$$\frac{\dfrac{MM'}{SM'} = \theta_h \times \text{a constant}}{\dfrac{MM'}{EM'} = \theta_g \times \text{a constant}}$$

and simplifying , we get

$$\frac{EM'}{SM'} = \frac{\theta_h}{\theta_g},$$

or

$$\theta_h = \frac{EM'}{SM'} \times \theta_g.$$

EM' is the distance from earth to Mars $r_{EM'}$ and SM' is the distance from the sun to Mars $r_{SM'}$ which can be found from your orbit plot. In terms of $r_{EM'}$ and r_{SM} the relation is

$$\theta_h = \frac{r_{EM}}{r_{SM}} \cdot \theta_g .$$

Q1 At what heliocentric longitudes does Mars cross the ecliptic plane ($\theta_h = 0$)? These are the *nodes.* Label these on your graph and show them at the correct places on your orbit plot. Join them with a straight line on the orbit plot. This line is called the *line of the nodes.*

Q2 Using the fact that Mars moves eastward along its orbit, find out which node is the ascending node. What is the *heliocentric longitude of the ascending node*, usually represented by the symbol Ω?

Q3 At what angle from the line of the nodes should the orbit reach its maximum latitude? This maximum value of the heliocentric latitude is the inclination i of the orbit. What is the value for i from your results?

Q4 What is the longitude angle measured along the

Table 8.4

Elements of Mars' Orbit		
Element	**Function**	**Mars' value**
a semi-major axis	determines average radius and period	1.52 A.U.
e eccentricity	describes shape of ellipse	0.093
i inclination	tilt of orbit plane from eccliptic plane	1.8°
Ω longitude of ascending	angle to where orbit crosses ecliptic plane from S to N	49.2°
ω argument of perihelion	orients orbit on its plane	286°

orbit in the direction of the planet's motion, between the ascending node and perihelion point for your orbit? This is called the argument of perihelion and is represented by ω.

ELEMENTS OF ORBIT

Now you have all of the elements necessary to decribe the shape and orientation of the Mars' orbit in space. These are shown in Figure 8.16 and are listed along with accepted values and their function in Table 8.4.

Compare your results with the tabulated results by finding the percentage error for each.

POSITION OF MARS

To find where Mars is along its orbit at any particular time, one more piece of data—the position at some zero time—is necessary. This is usually given as the date at which the planet passes the perihelion and can be found from your orbit plot. Then, knowing the period of the orbit, you can calculate the planet's position in the orbit *at any time* in the past or future.

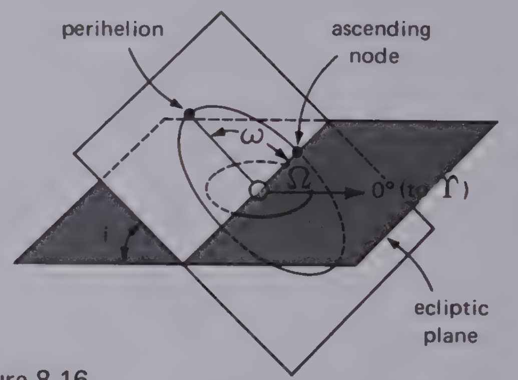


Figure 8.16

Q5 What is the time of passing perihelion for your Mars' orbit?

A THREE-DIMENSIONAL MODEL

Make a three-dimensional model of Mars' orbit as shown in the introduction to the experiment.

The elements for other planetary orbits are given in the *Observer's Handbook* and you could use them to build models of any of the planetary orbits.

Activities

> The divine voice that calls men to learn astronomy is, in truth, expressed in the universe itself, not by words or syllables, but by things themselves and by the agreement of the human intellect and senses with the ensemble of celestial bodies and phenomena.
>
> J. Kepler

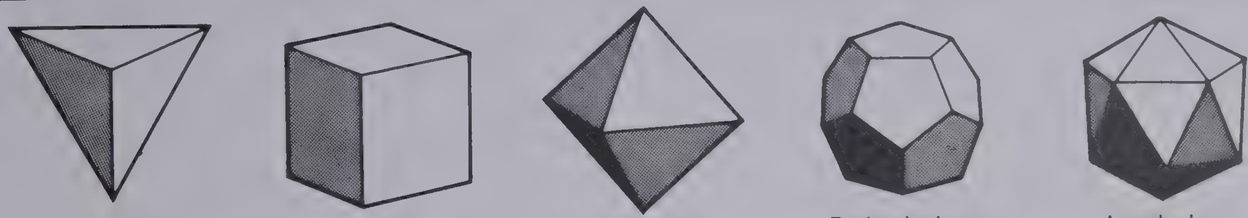


Figure 8.17

Activity 8.1 Five Platonic Solids

One of Kepler's attempts to find a model of the Universe made use of the five regular solids of Plato—the tetrahedron, cube, octahedron, icosahedron, and dodecahedron.

Kepler explained the spacing of the planetary orbits in terms of these "perfect" solids by nesting them inside one another separated by spheres.

You can make your own models of these solids from paper strips as shown in the *Mathematical Games* section of the September 1971 issue of *Scientific American.* The instructions are too lengthy to be included here but this issue should be available in a nearby library.

Once you have the solids constructed, it will be easier for you to visualize Kepler's model. It is described in Fred Hoyle's book *Astronomy* as follows:

> Imagine a cube inscribed inside a sphere. Now inscribe a sphere inside the cube . . . inside the second sphere, inscribe a tetrahedron . . . Then inside the tetrahedron inscribe a third sphere. Next inscribe a dodecahedron inside the third sphere. Now a fourth goes inside the dodecahedron, and inside this fourth sphere comes an icosahedron. A fifth sphere is added inside the icosahedron and then comes an octahedron inside the fifth sphere. Finally comes a sphere inside the octahedron, although Kepler found it better to cheat at this last stage and to place a mere circle inside the octahedron.

The radii of the spheres obtained in this way were quite close to the Copernican values of the orbits of the planets as shown.

Table 8.5

Planet	Kepler's Value	Copernican Value
Mercury	0.56	0.38
Venus	0.79	0.72
Earth	1.00	1.00
Mars	1.26	1.52
Jupiter	3.77	5.22
Saturn	6.54	9.17

Kepler was not satisfied with the degree of agreement between his model and observed data and so went on to use double spheres separated by the solids to improve his results. The attempt to refine his model illustrates Kepler's perseverance and it was this very perseverance which eventually led Kepler to discover his laws which proved so extremely important in giving a correct description of the solar system.

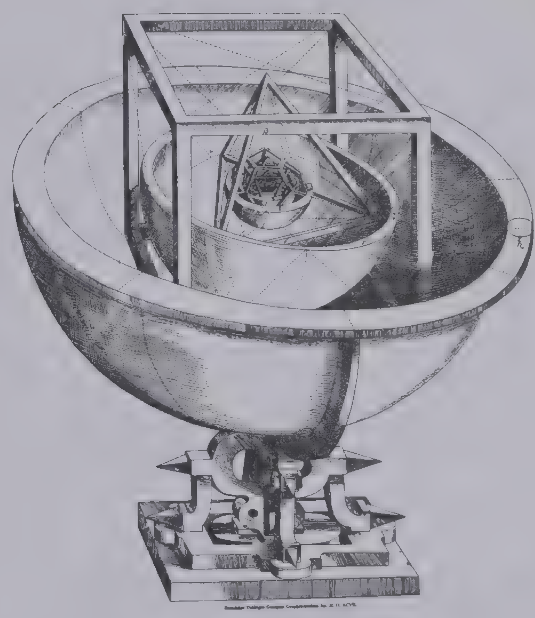


Figure 8.18

Q1 Why are there only 5 regular solids? Would it be possible to construct other closed, symmetric shapes with all faces congruent? Try to do so.

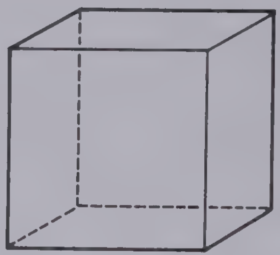


Figure 8.19

Q2 Euler's Theorem. For any convex polyhedron, the number of vertices (corner points) m, plus the number of faces n, minus the number of edges l, is equal to 2; that is $m + n - l = 2$.

For example, in a cube

$$m = 8$$
$$n = 6$$
$$l = 12,$$

and $$m + n - l = 8 + 6 - 12 = 2.$$

Show that this relation is true for the other four regular solids.

It is also possible to prove that it is *impossible* for more than five regular polyhedra to exist in three-dimensional space. You should try to demonstrate for yourself why this is so. Check your proof by referring to L.A. Lyusternik, *Convex Figures and Polyhedra*, D. C. Heath and Co., 1966.

Activity 8.2 Kepler's Celestial Music

Kepler developed an intriguing theory to correspond to the planetary orbits. He suggested that the planets acted in harmony as if each were emitting a sequence of musical notes. The pitch of each note was proportional to the speed of the planet. The range of the notes depended on the variation in the distance of the planet from the sun (the orbit eccentricity). By using the known orbit sizes, eccentricities, and periods he created the "tune" shown in Figure 8.20.

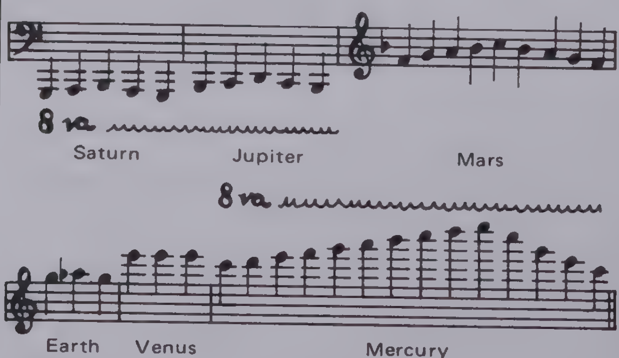


Figure 8.20

Study these sequences and comment on how each tune relates to the orbit shape and the behaviour of each planet in its orbit. You can compare your deductions with the information about planetary orbits in the text, or in the *Observer's Handbook*.

Examine the following table comparing results inferred from Kepler's harmonic model with Tycho's actual observations (taken from F. Hoyle, *Astronomy*).

	Harmonic		Tycho	
Planet	Aphelion Distance (A.U.)	Perihelion Distance (A.U.)	Aphelion Distance (A.U.)	Perihelion Distance (A.U.)
Mercury	0.476	0.308	0.470	0.307
Venus	0.726	0.716	0.729	0.719
Earth	1.017	0.983	1.018	0.982
Mars	1.661	1.384	1.665	1.382
Jupiter	5.464	4.948	5.451	4.949
Saturn	10.118	8.994	10.052	8.968

The agreement is amazing. Do you think there was any physical basis to Kepler's musical theory?

Another example of music which was inspired by the solar system is Gustav Holst's *The Planets*. You might like to try to compose your own music using Kepler's tunes as themes.

Activity 8.3 Titius-Bode Relation

An interesting relationship which seemed to correspond to the orbit radii of the planets, was first proposed by Titius in 1766 and promoted by Bode in 1772. The rule is expressed by the following simple formula. For each planet, begin with 4, then add a number which varies from planet to planet; for Mercury the number is zero, for Venus 3, for Earth 6, for Mars 12 and so on. Then divide the sum by 10 to give you the mean distance of the planet to the sun in astronomical units (A.U.). In algebraic form:

The average orbit radius, $R_{av} = \frac{n+4}{10}$

where $n = 0,3,6,12,24, \ldots$

The relation, when proposed, gave results amazingly close to the accepted values for Mercury, Venus, Earth, Mars, Jupiter, and Saturn.

Use the relationship to calculate the distances for the various values of n in the sequence and compare your results with the orbit radii of the planets given in the text on page 40.

Q1 For how many planets does the relation work?

You will find that the relation does not seem to work based on the planets known in 1766 for the cases where $n = 24$ and where n is greater than 96. However, at the time, most astronomers believed in the relation, and the later discovery of Uranus ($n = 192$) in 1781 seemed to justify their belief. This prompted a systematic search for the "missing" planet at 2.8 A.U. ($n = 24$) and in 1801 a large *asteroid,* Ceres, too small for a planet, was discovered at this distance. Since then many hundreds of asteroids have been discovered in the asteroid belt in the same region.

Q2 Research the history of the discovery of other planets and see how close their distances are to the prediction of the *Titius-Bode Relation.*

Q3 This relation is sometimes incorrectly called *Bode's Law.* Why is this relation not a full-fledged scientific law? Discuss.

Activity 8.4 Conic Sections

Get a model of the conic sections from your mathematics teacher. It is a cone cut into sections by planes at various angles as shown in Figure 8.21.

Identify each of the conic sections (parabola, hyperbola, ellipse, and circle) and determine the orientation of a plane with respect to the cone, which makes each section.

Each section represents a curve. An object acted on by a central force can travel along any one of these curves depending on the force and its range of speed. Consequently the sections are useful for describing satellite and planetary orbits. If you are interested in the speeds required for various satellite orbits around the earth, see *Orbital Space Flight* by Howard S. Seifert and Mary Harris Seifert, Holt, Rinehart and Winston.

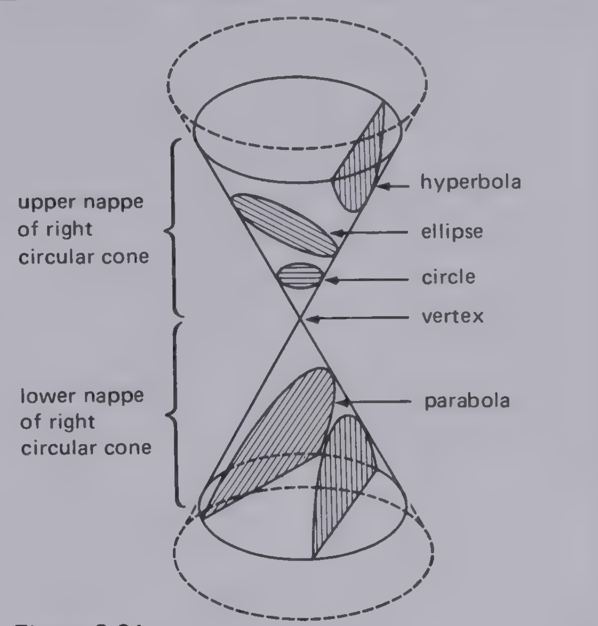


Figure 8.21

Activity 8.5 Observing with a Telescope

You can learn a great deal about the heavens with naked-eye observation, but, as Galileo discovered, many surprising and interesting details become visible with a telescope. Binoculars are also useful if a telescope is not available. You should plan to look for some of the features outlined below during some observing sessions. If you can obtain a copy of Galileo's *Starry Messenger* you can compare some of your observations in this activity with Galileo's sketches and descriptions in his famous book.

Use *The Observer's Handbook* to find more information about the best times for observing various features. NASA photographs (request *NASA Publications List* from National Aeronautics and Space Administration, Code FGC-1, Washington, D.C. 20456, U.S.A.) of some of the planets and of the moon can be useful to supplement your observations.

THE MOON

Great detail can be seen on the moon because it has almost no atmosphere to distort the view, it is close to us, and it is very bright. The moon's features are visible mainly because of shadows which are most

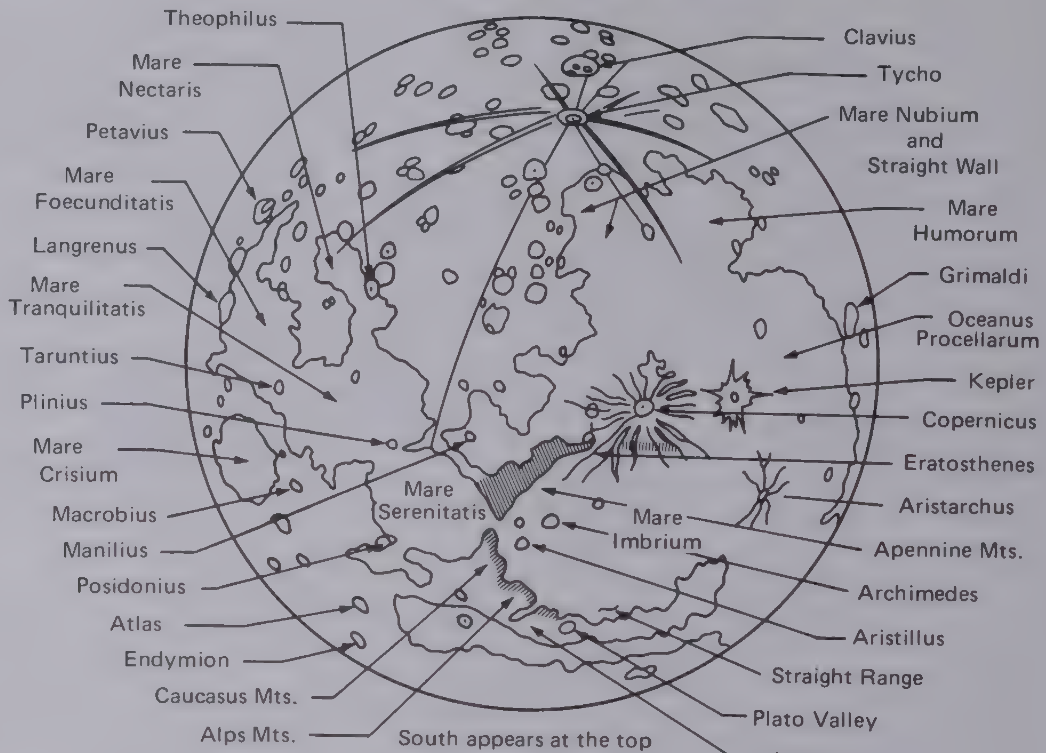


Figure 8.22 Map of the Moon

prominent around the first and last quarter. You should be able to see craters, some as large as 290 km across (Bailly), ringed by mountain ranges. The largest lunar features are the so-called seas (Maria). There are 14 of these large dry planes on the visible side of the moon and they form the features of the "man in the moon". The largest, *Mare Imbrium,* is about 1100 km in diameter. The best shadows and clearest features are along the terminator, a line which divides the sunlit from the dark portion. The terminator shifts as the sun rises on the moon. Long shadows near the terminator indicate prominent surface features such as mountains.

Observe and sketch features of a crescent moon and compare with a lunar map. Eclipses occur occasionally and are worth watching. A series of exposures on the same film with a tripod-mounted camera, taken at regular intervals during the eclipse, provides an excellent record. See the *Observer's Handbook* for the dates and times of eclipses. Also see the *Lunar Atlas* edited by D. Atler and published by Dover Publications for excellent photographs of the moon's features.

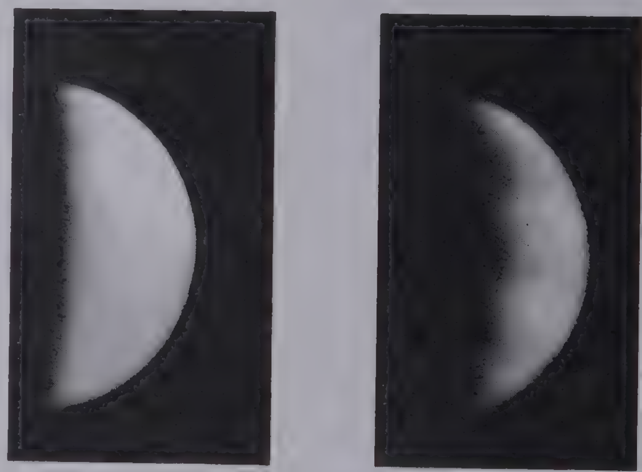


Figure 8.23

VENUS

Venus is shrouded by dense clouds so that no surface features are visible with most telescopes. However, you can observe the phases of Venus which are not obvious without a telescope. Venus is seen best as a morning star just before sunrise or as an evening star just after sunset.

Figure 8.24

MARS

Mars resembles a yellow-orange ball. Surface features cannot be seen with a small telescope. Mars does not go through phases.

Figure 8.25

JUPITER

Jupiter's disc is crossed with a cloud belt but with a telescope you should be able to see a darker region called the *Great Red Spot* near the equator of Jupiter. Galileo first observed four satellites or moons of Jupiter (actually there are 12). If you observe Jupiter on several successive evenings, you will see the configuration of the moons change. If you make a careful record—a series of sketches as shown in Figure 8.26—you can deduce the period of these satellite orbits.

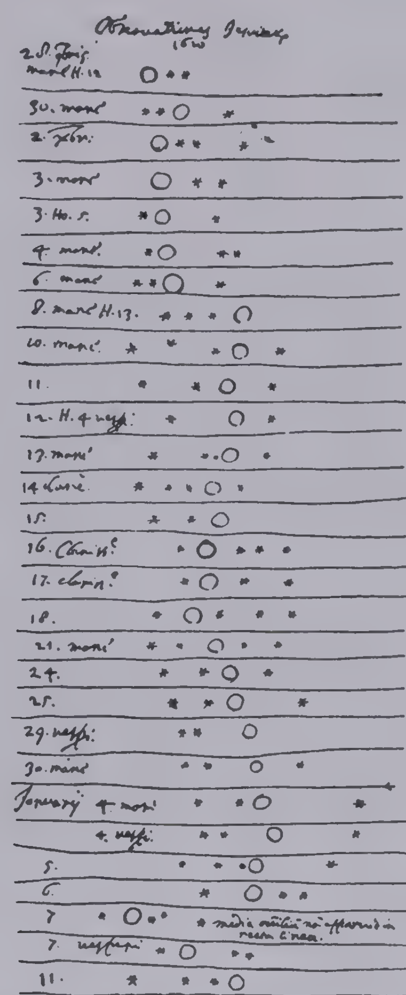


Figure 8.26

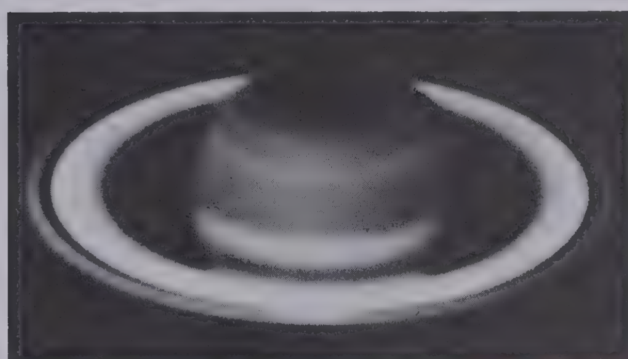


Figure 8.27

SATURN

The most outstanding feature of Saturn is its rings, which will be clear with a telescope. The disc is similar to Jupiter's without the "spot".

STARS

The number of visible stars increases tremendously with the power of your binoculars or telescope. Each looks like a point of light which may twinkle due to earth's atmosphere. The following features are particularly interesting.

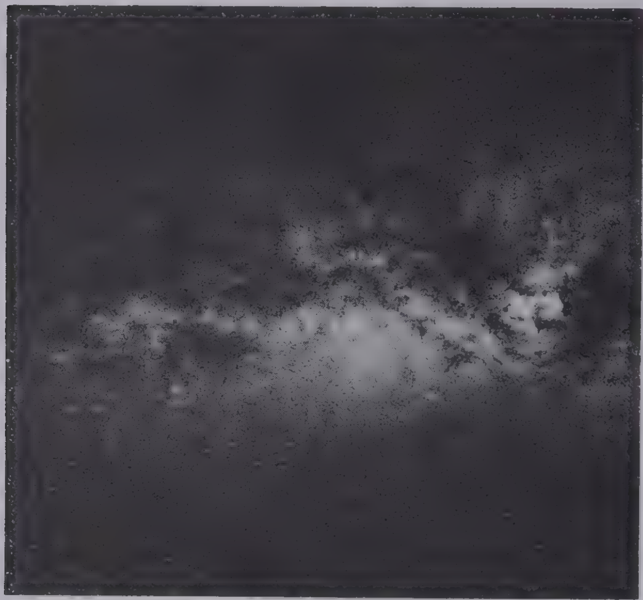


Figure 8.28

Our Galaxy (The Milky Way). The stars are concentrated along a band of light which circles the sky. This is simply the light from a myriad of stars that appears lined-up in our flattened galaxy as we observe it edge on. It is particularly bright in Cassiopeia and Cygnus.

Double Stars (Binaries). The first double star discovered in 1650 was Mizar (ζ Ursa Major), the second bright star in the handle of the Big Dipper. It is visible with a telescope.

Variable Stars. These stars vary in intensity with a definite period. Look for Algol in Perseus, south of Cassiopeia. It is about as bright as Polaris for 2 1/2 days, then becomes dimmer for 5 hours, and then brightens again to its former brightness in the next 5 hours. The total period is 2 days, 20 hours, 49 minutes. Algol is an *eclipsing variable*—the diminution in its brightness caused by a periodic eclipse by a dimmer companion binary. There are many other types of variable stars. (See *Making and Using a Telescope* by Wilkins and Moore, published by Eyre and Spottiswoode Ltd., London, for more details.)

Figure 8.29

Nebulae. The best example is M.42 Orionis—the sword handle below Orion's belt. It can be seen as a filmy patch. Orion is up in the winter months. Use low power. Also look for the Great Nebula in Andromeda which is high in the western sky in the early evening in December. Use low power. Photographs of Nebulae provide some of the most beautiful sights in astronomy. (See *Exploration of the Universe* by G. Abell for photographs and more information about nebulae.)

Figure 8.30

Clusters. One beautiful example of a group of physically connected stars is the Pleiades, or Seven Sisters in the constellation of Taurus, the Bull. Six or seven bright stars can be seen with the naked eye, but when you turn a telescope to them you will see many more. Use low power. Also look in Taurus for the Hyades, a faint V-shaped group marking the face of the bull. The Pleiades and Hyades are open clusters. An example of a globular cluster is M.13 in the constellation Hercules. It is visible to the naked eye and some detail emerges with a telescope.

Activity 8.6 Observing Sunspots

Sunspots, dark speckles on the sun's disc, can be observed with a telescope.

DO NOT LOOK AT THE SUN THROUGH THE TELESCOPE

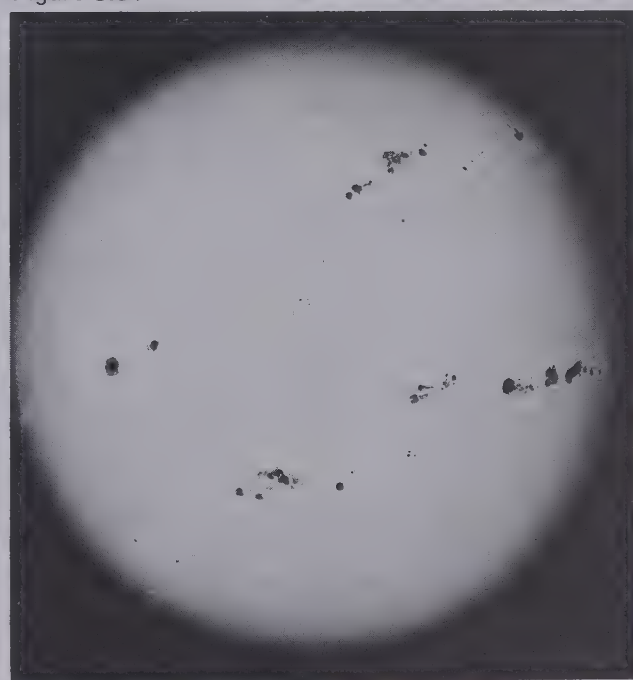
A split-second of viewing the sun through the telescope can blind your eye. Even observing through a filter fixed to the eyepiece can be dangerous, as they have been known to split due to the tremendous concentration of heat.

To see the sunspots, project the image formed by the telescope on a screen about two feet from the eyepiece. It is a good idea to stop part of the sun's rays before they enter the telescope with a paper disc with a hole at the centre, mounted on the end of the telescope. A two-inch opening should be sufficient.
Focus the telescope and trace the spots. (Remember the image is inverted by the telescope.) Figure 8.31 is a photograph of the sort of thing you might see.

Examine the spots. You may find the spots often occur in pairs oriented approximately east-west. By measuring across the sunspot and comparing with the diameter of the sun's image, you can calculate the size of some of the larger spots. (Some may be over 100,000 km in diameter.)

Most of the spots are short-lived, but some will grow and last for several days or weeks. By observing the sun on successive days you may be able to detect motion of the spots. It is even possible to calculate the rate at which the sun rotates on its axis by measuring the east-west motion of the spots from your sketches. Try it.

Figure 8.31



Activity 8.7 Trial of Copernicus

Although Copernicus was never put on trial, his views were revolutionary. Along with several others in your class, prepare a prosecution and defense for Copernicus and put him on trial before the rest of the class. You could select a jury and subpoena "expert" witnesses from the class.

Activity 8.8 Galileo by Bertolt Brecht

Read Brecht's play and present part of it to the class. Brecht's play presents a point of view about Galileo, his work and motivation which is not shared by all who have studied his life. Some references which may be useful for comparison are:

G. de Santillana, *Crime of Galileo.* University of Chicago Press.
L. Fermi, *Galileo and the Scientific Revolution.* *"Galileo: Antagonist"* and *"Galileo Galilei: An Outline of His Life"* from the April 1966 issue of the *Physics Teacher.*

Activity 8.9 Velikovsky and Galileo

Immanuel Velikovsky and Galileo Galilei are two men of science who, although separated in time by more than three centuries, have a great deal in common.

You already know how Galileo proposed theories which countered established views, and how he was called to account for doing so. Velikovsky is still alive, and he too has published theories which have been considered heretical by the scientific establishment. Although Velikovsky has never been put on trial in a court of law, he has been shunned for years. In the same way as Galileo's discoveries were confirmed bit by bit, some of Velikovsky's predictions are now being proved true.

Find out more about these two men. Compare their personalities, theories, and situations. Some good references, along with those in Activity 8.8 are:

Galileo Galilei, *Dialogues Concerning the Two Chief World Systems* trans. S. Drake, University of California Press.
Galileo Galilei, *Dialogues Concerning Two New Sciences* trans. H. Crew and A de Salvio, McGraw Hill.
G. de Santillana, *The Crime of Galileo,* University of Chicago Press.

I. Velikovsky, *Worlds in Collision,* Doubleday 1950.
I. Velikovsky, *Earth in Upheaval,* Doubleday 1955.
A. de Grazia (ed), *The Velikovsky Affair,* University Books 1966.

An entire issue of *Pensée* (May, 1972) gives an account of Velikovsky's situation. Back copies can be obtained by writing *Pensée,* P.O. Box 414, Portland, Oregon 97207, U.S.A.

Activity 8.10 Debate

There are several scientific issues confronting society which are open to debate. Some of these issues were as important in the development of science in the times of Copernicus, Galileo, and Newton as they are today. You could prepare and present a debate on some of these issues using information which you have learned in this course. You could choose your own resolution or use one of the following as a basis for debate.

Resolved: The scientist must have absolute freedom in his research and should be concerned with neither the morality of the uses to which his discoveries may be put, nor the morality of the research itself.

Resolved: The truth of science is completely objective.

Resolved: The goal of science should be humanitarian. Scientific projects which do not benefit society directly should be abandoned.

Find out the rules and procedures of debate from your English teacher and present your debate to the class.

Chapter 9. The Unity of Earth and Sky

Forces which keep objects in curved paths here on earth, act in the same way as forces which guide objects moving in the solar system. In this chapter, the experiments deal with the effects of these forces.

Experiment 9.1 Centripetal Force

An object will move in a circle, only if a force toward the centre of the circle acts continuously on it, to divert it from its "natural" straight line path. This centre-seeking force is called the *centripetal force.*

In this experiment you will discover how the centripetal force F_c required to keep an object in a circular orbit, depends on the mass of the object m, its speed v, and the radius of the orbit R.

The experiment can be done with the apparatus shown in Figure 9.1.

Figure 9.1

Procedure

The object must be swung at a constant frequency in a horizontal circle so that the string is as close to horizontal as practical at all times. Keep the stick vertical and restrict its motion as much as possible.

To set the frequency, use a metronome or a tape recorder which plays prerecorded beats equally spaced in time. (It is more convenient to measure the orbit frequency rather than the speed. You can convert to speed later in the experiment.) Adjust the length of the string and the position of the spring scale so that the orbit radius R, is 0.50 m. Keep this length constant. (A masking tape tag on the string can be used to mark the string's position.) Once the object is orbiting correctly, read the force F_c which is in newtons, being applied by the spring scale. Keep it swinging and take two more force measurements and then find an average. Tabulate your results as shown in Table 9.1.

Table 9.1

Trial	Object's Mass, m (kg)	Orbit Frequency, f (Hz)	Orbit Radius, R (m)	Centripetal Force, F_c (N)
1				
2				
3				
.				
.				
.				

In order to find how F_c depends on each factor, repeat the experiment *changing only one quantity at a time.* For example, you could double the mass by adding a similar object while keeping the other quantities constant. In later trials, other quantities could also be doubled, tripled, or halved until you have sufficient data to reach conclusions.

Analysis

Q1 How does a change in m affect F_c if f and R remain constant? Write a formula based on your data which describes the relation between F_c and m.

Q2 How does a change in R affect F_c if f and m are kept constant. Express this with a formula.
Q3 How does a change in f affect F_c if m and R are kept constant. Write a formula to show the relation.
Q4 What change would you predict for F_c if
(a) m only were doubled?
(b) f only were doubled?
(c) R only were doubled?
(d) if m, f, and R all were doubled simultaneously?
Check your answers by consulting Table 9.2.

Table 9.2

Centripetal Force			
m (kg)	R (m)	f (Hz)	F_c (arbitrary units)
1	1	1	X
2	1	1	2X
1	1	2	4X
1	2	1	2X
2	2	2	16X
1	3	1	Complete these
3	1	1	
1	1	3	
3	2	1	
1	1/2	2	

Q5 Extend the reasoning you used in Q4 to complete the following table. (Units for F_c are arbitrary.)
Q6 Find a formula expressing the relationship between F_c and m, R, and f combined. Compare with the expression derived in the text on page 63.
Q7 Rewrite the formula expressing F_c in terms of m, R, and the orbit speed v.

Experiment 9.2 Stepwise Approximation to an Orbit*

According to Newton's Theory of Universal Gravitation, any comet or satellite orbiting a body such as the sun is continuously acted upon by a force of attraction between the two bodies. This gravitation force $\vec{F}$ changes the satellite's velocity $\vec{v}$ in direction and magnitude. To find the shape of the orbit produced by such a force acting continuously, Newton used the calculus which he had developed. Although you probably do not know any calculus, you can approximate such an orbit using fairly simple mathematics, by breaking the orbit down into a series of small steps.

We shall assume that the force acts toward the sun discontinuously, that is, as a series of blows on the satellite at 60-day intervals. In between blows, the satellite travels in a straight line.

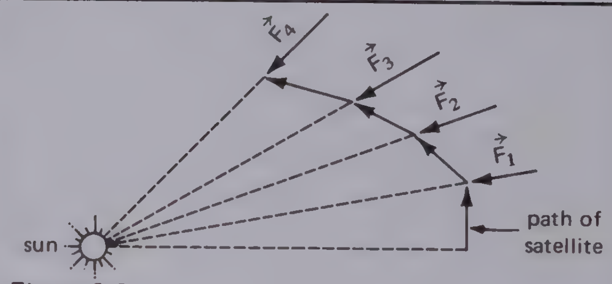


Figure 9.2

Each blow will cause the satellite's $\vec{v}$ to change according to Newton's Second Law.

$$\vec{F} = m\vec{a}$$
$$= m \cdot \frac{\Delta\vec{v}}{\Delta t}.$$

If the mass m, of the satellite and time-interval Δt, are constant for each step in the orbit, then $\Delta\vec{v}$ will vary directly as $\vec{F}$ and be in the same direction.

After each blow, the satellite's final velocity $\vec{v}_f$ will be the vector sum of its initial velocity $\vec{v}_i$ and $\Delta\vec{v}$. This vector sum can be found graphically as shown in Figure 9.3.

Also, the final velocity for the first interval becomes the initial velocity for the second interval and so on.

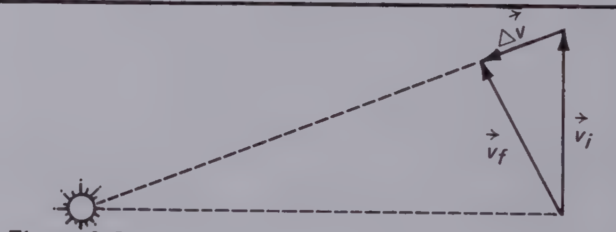


Figure 9.3

*A similar experiment by Dr. Leo Lavatelli, appears in the *American Journal of Physics*, Vol. 33, p. 605.

SIZE OF THE ORBIT

We shall assume that initially the satellite is 4.0 A.U. from the sun with a velocity $\vec{v}_o$ of 2.0 A.U. per year (approximately 20,000 mph = 32,000 km/hr) perpendicular to the line joining the sun and the satellite.

A speed of 2.0 A.U. per year is the same as $\frac{2.0 \times 60}{365}$ A.U./60 days, or 0.33 A.U./60 days. Therefore, during the first 60-day interval, the satellite's displacement will be 0.33 A.U. In general, for every 60-day interval, the displacement in A.U. will be equivalent to the velocity expressed in A.U./60 days and vice versa.

SCALE

Using a scale of 1.0 A.U. = 6.0 cm, the orbit plot will fit nicely on a piece of paper 16″ X 20″ which can be made from four 8 1/2″ X 11″ sheets taped together.

Q1 Using this scale, what vector length will represent the satellite's initial velocity $\vec{v}_o$?

CALCULATING $\Delta\vec{v}$

As mentioned above, $\Delta v \propto F$. From Newton's *Law of Gravitation,* we know that F depends on the distance R, between the two bodies. F is inversely proportional to R^2. ($F \propto 1/R^2$.) Consequently $\Delta v \propto 1/R^2$ also.

The conditions are set in this experiment so that $\Delta\vec{v}$ = 1.0 A.U./60 days, directed toward the sun, where R = 1.0 A.U. Using the *Inverse Square Law,* you should be able to calculate Δv for any value of R at the end of each interval. Try the following examples.

Q2 (a) If R = 2.0 A.U., what is Δv?
(b) If R = 2.5 A.U., what is Δv?

This procedure is time consuming. You may use instead a graphical method which we shall call your Δv calculator. In Table 9.3 are values of Δv for various R values.

To make your Δv calculator, plot Δv versus R on a single sheet of graph paper. Fold under the margin below the R axis of your graph as shown in Figure 9.4.

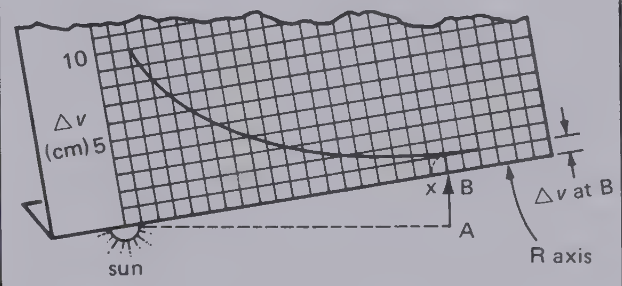


Figure 9.4

PLOTTING THE ORBIT

Locate the sun's position at the centre of the page and measure the distance to the satellite's initial position A (24 cm) to the right of the sun as shown in Figure 9.5.

Draw a vector to scale from A representing $\vec{v}_o$ in A.U./60 days. At the end of the 60-day interval, the satellite's position will be at B, the tip of $\vec{v}_o$.

Table 9.3

Comet orbit data		**Corresponding data for ΔV calculator**	
Distance from sun (A.U.)	**Velocity change (A.U./60 days)**	***R* (cm)**	**ΔV (cm)**
0.8	1.57	4.8	9.4
0.9	1.23	5.4	7.4
1.0	1.00	6.0	6.0
1.2	0.69	7.2	4.1
1.5	0.44	9.0	2.6
2.0	0.25	12.0	1.5
2.5	0.16	15.0	1.0
3.0	0.11	18.0	0.7
3.5	0.08	21.0	0.5
4.0	0.07	24.0	0.4

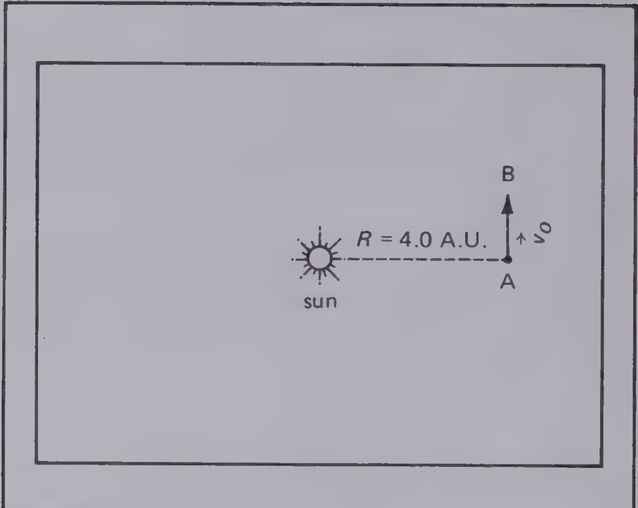


Figure 9.5

Now to find $\Delta\vec{v}$ due to the first blow at B you will use your Δv calculator. Set it so that the origin of the graph coincides with the sun's centre, and rotate the graph so that the R-axis goes from the sun to the satellite's new position (B in the first case). This is illustrated in Figure 9.4.

Measure Δv from the graph with dividers or compasses and lay off this distance BX along BS.

Find the velocity for the next interval by completing the triangle ABX. AX represents the vector sum

$$\vec{v}_1 = \vec{v}_0 + \Delta\vec{v}_1.$$

Now move v_1 so that its tail is at B. Be careful to get both v_1 vectors with the same magnitude and direction. The tip of v_1 will now be at C, the new position of the satellite as shown in Figure 9.6.

Repeat the entire procedure finding $\Delta\vec{v}$'s and $\vec{v}$ for the next interval and so on, so that you establish a series of points $D, E, \ldots$ along the satellite orbit.

Fourteen or fifteen steps should take you around the sun and approximately 25 steps should complete the orbit. Your orbit may not close exactly. This may be due to your inaccuracy or to the long Δt interval used. If it almost closes, approximate the closed orbit by using symmetry.

CHARACTERISTICS OF THE ORBIT

Q2 Calculate or measure the following characteristics of your orbit.

(a) semi-major axis a
(b) eccentricity e
(c) period T (in years)
(d) perihelion distance (in A.U.)
(e) ratio $\dfrac{v \text{ perihelion}}{v \text{ aphelion}}$

Q3 Is your orbit elliptical? Demonstrate.

Q4 Does the orbit satisfy Kepler's *Law of Areas?*

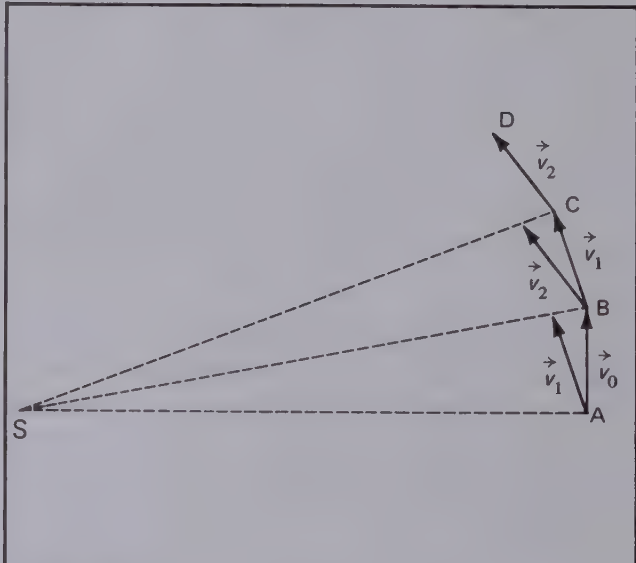
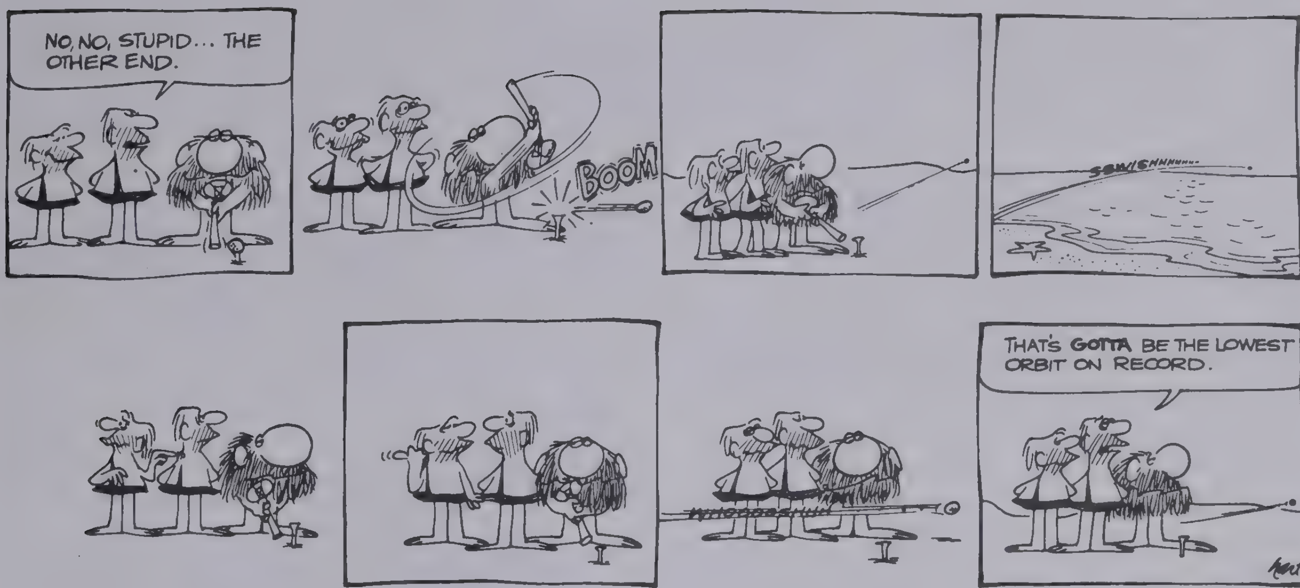


Figure 9.6

Activities

"I derive from the celestial phenomena the forces of gravity with which bodies tend to the sun and the several planets. Then from these forces, by other propositions which are also mathematical, I deduce the motions of the planets, the comets, the moon and the sea. . . .

Sir I. Newton



Activity 9.1 Penny and Coat Hanger

Here is a tricky demonstration related to circular motion which you can try. Bend a coat hanger into the shape sketched. The hook should be bent so that it points to the opposite end of the diamond.

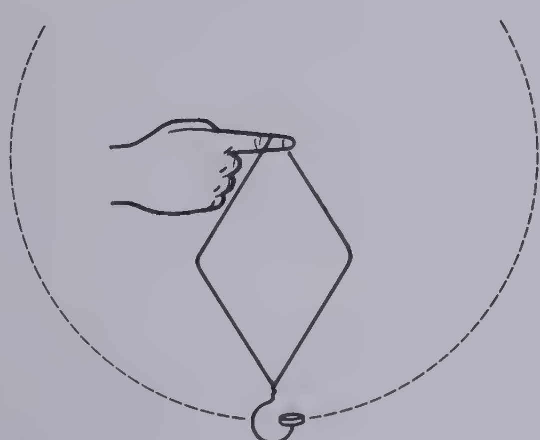


Figure 9.7

Dangle the hanger from your index finger and carefully balance a penny on the tip of the hook.

Once you have it balanced, if your nerves are still steady, begin to oscillate the hanger to the left and right without losing the penny. Once you have the rhythm, increase the swing until you can swing the hanger all the way around in a vertical circle. Continue this circular motion. You should be able to keep the penny balanced for several revolutions.

Now consider why this demonstration worked.

Q1 What force kept the penny on the hook when

(a) the hanger was vertical?

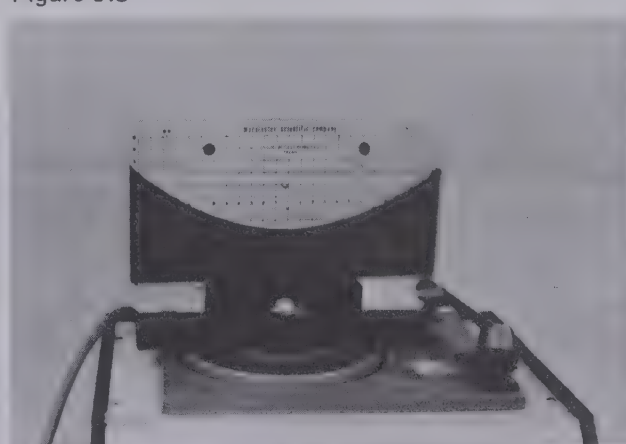
(b) the hanger was moving in a circle?

Discuss the answer to this question carefully. You could use force diagrams to consider the situation when the penny was in the various positions shown in the diagram.

Activity 9.2 Centripetal Acceleration

The liquid-surface accelerometer can be useful in studying centripetal acceleration. Place an accelerometer on a turntable as shown in Figure 9.8.

Figure 9.8



When the turntable is rotated, the surface becomes curved as the liquid is "thrown" from the middle to the ends of the accelerometer in much the same way as water is spun from a spinning automatic washer. It is difficult to see this shape, but you can study it more closely if you take a short-exposure photograph as the accelerometer is rotating. Try it for different speeds.

The shape of the water surface is parabolic. To find the acceleration at any point along the surface, you can draw a tangent to the surface and measure its slope. The acceleration is given by the relation $a =$ slope $\times$ a_g. (See theory of an accelerometer Unit 1, page 141.)

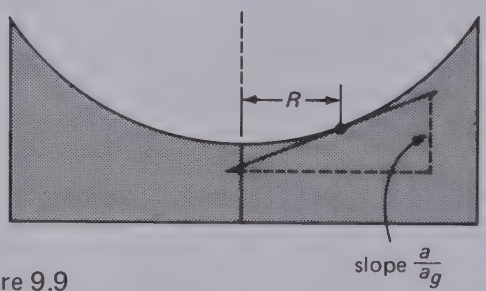


Figure 9.9

Find the centripetal acceleration at various radii R from the centre of the accelerometer for one frequency. Compare your results with the predictions of the equation

$$a_c = 4\pi^2 Rf^2.$$

You can also measure accelerations at the same radius for various rotation frequencies and compare your results with predictions from the same equation.

Activity 9.3 Building a Cavendish Apparatus*

The fact that a gravitational force exists between all objects even small ones such as bricks, can be shown by an experiment set up similar to the one used by Henry Cavendish in 1798. If sufficient care is used in assembling the apparatus, a measurement of the value of the gravitational constant G can be made.

Find a stairwell or a place with a very high ceiling (at least 5 m high) where there is very little or no traffic.

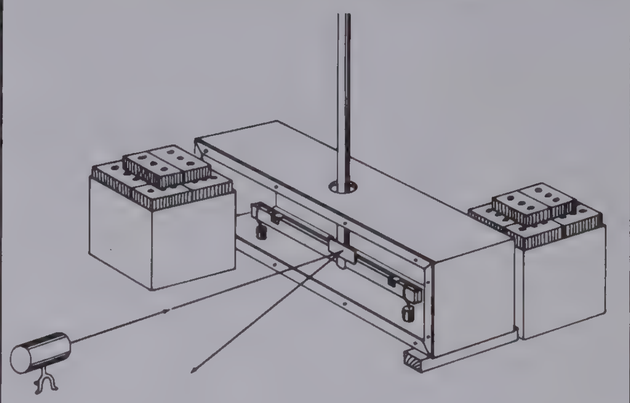


Figure 9.10

Construct a torsion pendulum by hanging 0.5 kg masses from the ends of two metre sticks clamped together for strength. Suspend the metre stick with a long piece of recording tape doubled and fixed to the ceiling. Enclose the pendulum and masses in a box with glass on one side to eliminate the effect of drafts.

Attach a mirror with plasticine to the centre of the sticks and set up a light source with a narrow beam which will reflect off the mirror to produce a spot on a nearby wall. Any movement of the torsion pendulum is amplified by the light-mirror arrangement.

Place two cartons each containing 50 kg of bricks or other masses on opposite sides of the 0.5 kg masses at each end of the torsion pendulum. Shift the cartons so that the distance between the centres of the bricks and the hanging masses is 25 cm.

Leave the apparatus undisturbed overnight to allow oscillations of the pendulum to die out. Then mark the position of the light spot on the wall. Move the cartons of bricks to opposite sides of the pendulum and adjust the spacing so that it is the same as before. Now the pendulum should twist in the opposite direction. Leave the apparatus again until the oscillations die out and mark the spot's new position on the wall. The difference in the initial and final positions of the spot is due to a gravitational force between the masses on the torsion pendulum and the cartons of bricks.

*Based on two articles in *The Crucible*
(1) W. G. Helps, *Crucible,* 11 (April 1966)
(2) , *Crucible,* 38, 39 (Jan. 1973)

If you wish to use the apparatus to measure G as Cavendish did, use the following theory. As the tape supporting the pendulum twists it raises the suspended masses. The work done by the gravitational force between the bricks and the suspended masses is equal to the gain in the masses gravitational potential energy as they are lifted (assuming all other energy losses are negligible). From this it can be found that

$$F_g = \frac{m a_g \, w^2 d}{3 \, L \, s^2},$$

where m = mass of suspended masses
a_g = acceleration due to gravity
w = width of the tape
s = separation of suspended masses
L = length of tape
d = displacement of the suspended masses.

From Newton's *Universal Law of Gravitation*

$$F_g = G\frac{M\,m}{r^2},$$

where M = total mass of the bricks
r = centre-to-centre distance between suspended masses and bricks.

Combining the two equations above,

$$G\frac{Mm}{r^2} = \frac{m a_g \, w^2 d}{3 \, L \, s^2}.$$

Substituting measurements from your experiment, you can solve for G. Compare your result with the accepted value of

$$G = 6.7 \times 10^{11} \frac{N\,.\,m^2}{kg^2}.$$

Suggest reasons for the difference between your value and the accepted value of G.

If you wish to find out how Henry Cavendish did the experiment, you can read his original account in *Great Experiments in Physics,* edited by Morris H. Shamos, published by Holt, Rinehart and Winston.

Activity 9.4 Halley's Comet

Halley's comet is one of the best known "visitors" to the solar system. It sweeps in from outer space intersecting the orbit planes of the planets every 76 years. Its last visitation occurred in 1910. It is interesting to construct a three-dimensional model of the orbit of Halley's comet showing the part of its orbit when it is closest to the sun.

Use two pieces of cardboard, one for the ecliptic plane, and one for the orbit plane of Halley's comet. On the card for the ecliptical plane, choose a point at the centre to represent the sun's position. Draw concentric circles to a scale of 10 cm = 1 A.U. to represent the orbits of Mercury, Venus, and Earth. Draw a straight line from the sun to the right on the card to show the direction toward the vernal equinox, (0 degrees longitude). Show the earth's position at equal intervals (about every 30 days) around the earth's orbit. (Remember that the earth's longitude increases almost 1 degree eastward each day or use the earth's positions shown on the earth orbit plot in Experiment 7.1.)

On the second card, also choose a point to represent the sun's position near the centre of the card and draw a line showing the direction toward the vernal equinox.

Table 9.4 shows the longitude and the distance from the sun to the comet during its last, closest approach in 1910.

Table 9.4
Halley's Comet 1910

Date	Heliocentric Longitude (degrees)	Distance Between Comet and Sun (A.U.)
Mar. 1	33	1.13
11	24	1.05
21	14	0.88
31	359	0.77
Apr. 10	333	0.63
20	303	0.59
30	272	0.63
May 10	248	0.77
20	232	0.88
30	220	1.05
June 9	212	1.13

Plot this portion of the comet's orbit on the card using the same scale as before. The resulting shape will be one end of the comet's elliptical orbit as shown in Figure 9.12.

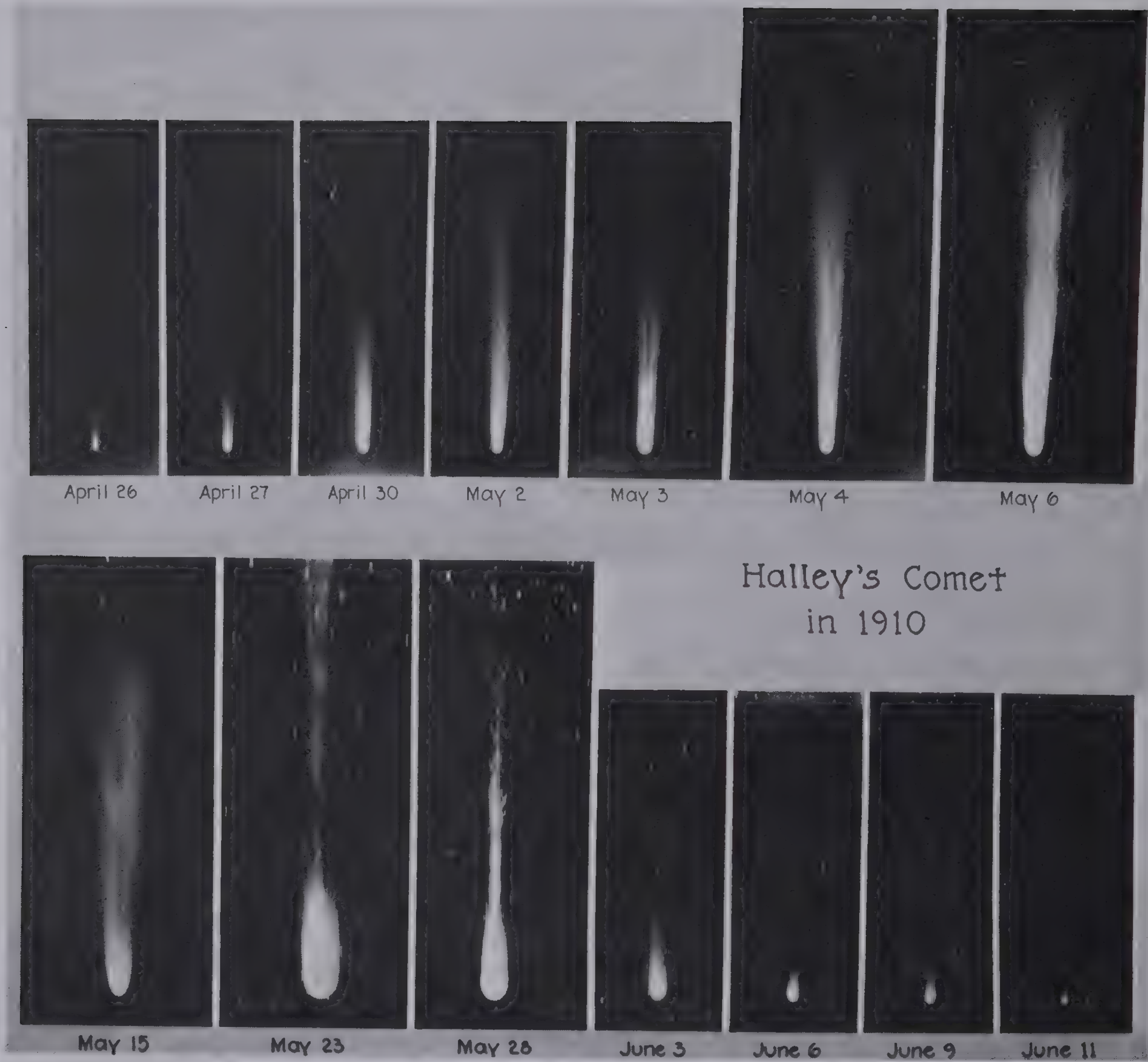


Figure 9.11

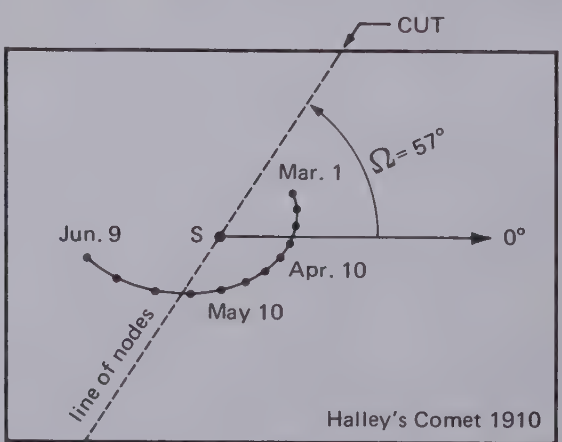


Figure 9.12

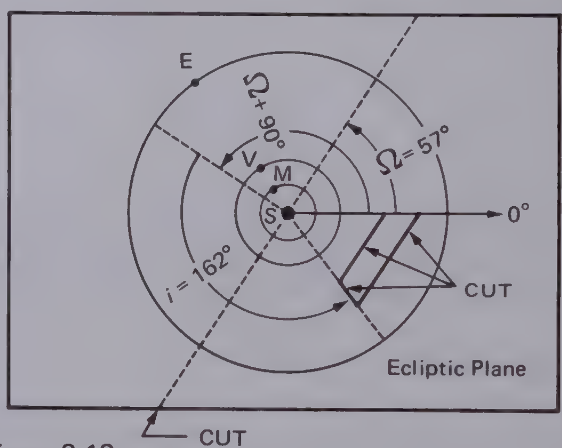


Figure 9.13

Q1 How does the direction of the comet's motion along its orbit compare with the direction of revolution of the planets (except Pluto)?
Q2 On approximately what date is the comet at perihelion?

To get the comet orbit oriented correctly with respect to the ecliptic, first locate the ascending and descending nodes as shown in Figure 9.12. The longitude of the ascending node $\Omega = 57$ degrees. Cut the comet orbit card along the line of the ascending node to the sun's position. Also mark the line of nodes on the ecliptic plane card and cut it from the opposite side to the sun's position as shown in Figure 9.13.
To complete the correct orientation of the comet orbit, it must be inclined at the proper angle to the ecliptic. This can be done with a flap cut in the first card as shown in Figure 9.13. The angle of inclination is measured from the line at $\Omega + 90^\circ$. For Halley's comet the angle of inclination $i = 162^\circ$. Measure the angles and then cut the flap as shown. Then bend it up to be used as a support for the comet orbit card.

Finally, slip the two cards together along the line of the nodes and tape the flap to hold the orbit planes at the correct inclination.

Examine the map showing the motion of Halley's comet and use your model to explain the features of the comet's motion. Also use it to answer the following questions.

Q3 A comet develops a tail due to the sun's radiation. The tail is directed away from the sun. Is it possible that the earth could have passed through the tail of Halley's comet in 1910 and if so on what date? How long would the tail have to be at this time to envelop the earth?
Q4 Why did the comet appear to move first westward, then remain almost motionless during April and finally eastward as shown on the map on page 68 of the text?
Q5 The eccentricity of the orbit of Halley's comet is 0.967. Use this and the perihelion distance to find the aphelion distance and the average radius (in A.U.) of the orbit.
Q6 Using Kepler's *Law of Periods,* find the period (in years) of the comet orbit.

Film Loop Notes

Film Loop 9.1 Jupiter Satellite Orbit

Galileo discovered 4 of the 12 satellites of Jupiter with his telescope in 1610. In this film loop, you will see the orbit of the innermost Jovian satellite, Io, in time-lapse photography done at the Lowell Observatory, Flagstaff, Arizona, with a camera mounted on a 24-inch refractor. Photographs were taken at one-minute intervals during seven nights. Each night only a portion of Io's orbit was photographed. These portions were spliced together to simulate one complete orbit. (Io had actually completed several orbits during these seven days.)

First, you will see a segment of the orbit. Jupiter is in the centre of the picture, and three of the satellites, including Io, move along an almost-straight line as we see the planes of their orbits nearly edge-on from the earth. Satellites moving to the left pass in front of Jupiter. This is called a *transit.* As they move to the right, they eventually pass behind Jupiter. This is called an *occultation.* Other satellites are out of the field of view.

Next, you see the dates during which the segments of the orbit of Io were photographed. The information of this sequence is summarized in the diagram. Other satellites moving at different speeds in their orbits suddenly appear and disappear while Io seems to move continuously in its orbit.

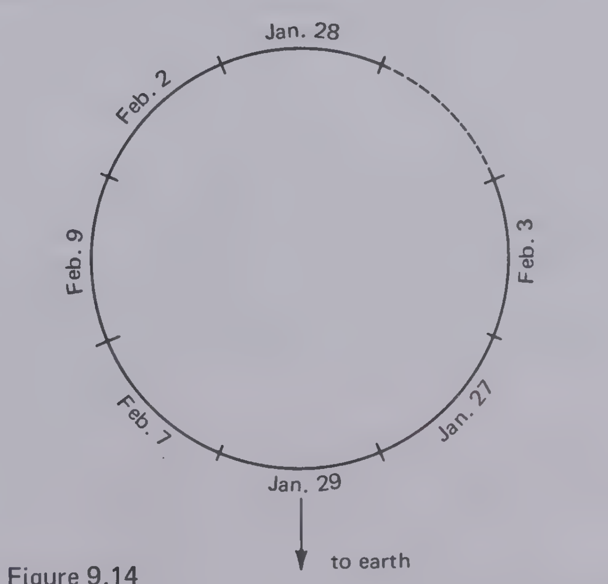


Figure 9.14

At the beginning of the orbit, indicated with marker lines, Io seems to be at rest. It is near its maximum eastern elongation. Another satellite, Europa, overtakes and passes Io. Then moving to the left, Io is joined by another satellite, Ganymede, and both have a transit at about the same time. They are invisible against Jupiter although you may be able to see a shadow of them on the left portion of the disc.

Io then moves to its western elongation, moves back to the right disappearing behind Jupiter, and finally reappears briefly before the end of the loop.

MEASURING PERIOD AND RADIUS

You can measure the period T and radius R of Io's orbit and from them, calculate the mass of Jupiter.

To measure T, you will need a stopwatch or a watch with a sweep-second hand. The time from when Io begins its transit until it disappears in its occulation, is the time for one-half of the orbit or $1/2T$. You can measure this time from the loop, but it must be converted to actual time. Since the film was exposed at one frame per minute and is projected at approximately 18 frames per second, time is compressed by a factor of $18 \times 60 = 1080$. You can multiply your measurement by 1080 to find $1/2T$ in seconds. The accepted value of Io's period is 1 day 18 hours and 28 minutes. Compare your results with this figure.

Io's orbit is practically circular ($e = 0.0000$). To find its radius from the loop, you can project the loop on a chalkboard. Mark its maximum eastern and western elongations and measure the apparent distance across the orbit. Also measure the equatorial diameter of Jupiter. To find the scale factor, you can use the fact that Jupiter's radius is 7.18×10^7 m. Now find the orbit radius of Io. Compare with the accepted value of 4.22×10^8 m.

Using Newton's *Law of Gravitation,* you can now calculate the mass of Jupiter. Compare with the accepted value of 1.90×10^{27} kg.

BIBLIOGRAPHY

Magazines

Pensée, May 1972, entire issue on Velikovsky.

Physics Teacher, April 1966, Galileo: Antagonist; Galileo Galilei: An Outline of Life.

Scientific American, August 1959, Amateur Scientist; September 1971, Mathematical Games.

Handbooks and Technical Data

American Ephemeris and Nautical Almanac, Superintendent of Documents U.S. Government Printing Office, Washington, D.C. 20402, U.S.A.

Huffer, Marasso, *Laboratory Exercises in Introductory Astronomy,* Holt, Rinehart and Winston, 1967

NASA Publications List, National Aeronautics and Space Administration, Code FGC-1 Washington, D.C. 20456, U.S.A.

The Observer's Handbook, Royal Astronomical Society of Canada, 252 College St., Toronto, Ont.

SC 1 and SC 2 Constellation Charts, Sky Publishing Corporation, 49 Bay State Road, Cambridge, Mass., U.S.A.

Texts

Hoyle F., *Astronomy,* Rathbone Books Ltd.

Lyusternik L.A., *Convex Figures and Polyhedra,* D.C. Heath and Co.

de Santillana G., *The Crime of Galileo,* University of Chicago Press

Galileo Galilei, *Dialogues Concerning Two New Sciences,* trans. H. Crew and A de Salvio, McGraw Hill

Velikovsky I., *Earth in Upheaval,* Doubleday

Abell, *Exploration of the Universe* Holt, Rinehart and Winston.

Fermi L., *Galileo and the Scientific Revolution*

Mayall and Mayall, *Sundials,* Charles T. Brantford Co., Boston

de Grazia A. (ed), *The Velikovsky Affair,* University Books 1966

Velikovsky I., *Worlds in Collision,* Doubleday

Brandwein Paul F., *You and Science,* Harcourt, Brace and World Inc.

Answers to End-of-Section Questions

Chapter 6

Q1 Altitude of Polaris equals latitude of observer
Q2 a) Counterclockwise circular motion about star Polaris. (15°/hour)
b) Westward motion along circ. of circle at about 15°/hr.
Q3 Circular clockwise motion (15°/hr.)
Q4 June 20 (6 h); Nov. 10 (15 h); Dec. 20 (18 h); Mar. 21 (0h)
Q5 Orion; approx. 12 hours
Q6 Before the sun by about 4 minutes.
Q7 47°
Q8 Discussion
Q9 a) 6 h
b) 12 h
c) 18 h
d) 0 h

Q10

Phase	*Time of Day (moon rise)*
new	morning
first quarter	early afternoon
full moon	early evening
third quarter	late evening

Q11 The orbits of the sun and moon do not lie in the same plane.
Q12 They are restricted to a zone in the sky near the sun.
Q13 Discussion
Q14 No. Planets are near the plane of the ecliptic, which crosses the southern (not northern) sky.
Q15 The problem considers only the positions the planets *appeared* to be at in the sky. They did not know where the planet really was since they did not consider the distances of these objects.
Q16 Discussion
Q17 Discussion
Q18 Discussion
Q19 Discussion
Q20 Discussion
Q21 Discussion
Q22 Discusion

Chapter 7

Q1 Discussion
Q2 Discussion
Q3 Discussion
Q4 Discussion
Q5 Discussion
Q6 Discussion

Chapter 8

Q1 Discussion
Q2 Kepler hoped that Brahe's precise observational data would confirm his model of the cosmos.
Q3 Brahe felt that Keplers great ability in mathematical analysis could be helpful in supporting Brahe's own model of the cosmos.
Q4 *Law of Elliptical Orbits*—the orbit of the planets about the Sun is an ellipse having the Sun at one focus.
Law of Equal Areas—the line joining the Sun to a planet sweeps out equal areas in equal times as the planet travels in its orbit.
Q5 These laws describe how planets move, not why.
Q6 In spite of his best efforts, Kepler could not get a model based on circular orbits to agree with Brahe's observational data.
Q7 At Perihelion
Q8 Discussion
Q9 Discussion
Q10 Discussion
Q11 Discussion
Q12 Discussion
Q13 Discussion
Q14 Discussion
Q15 Discussion

Chapter 9

Q1 Discussion
Q2 Discussion
Q3 a) Force decreases by $(1/2^2)$
b) Force decreases by 1/9 $(1/3^2)$
c) Force increases by 4 $(1/½^2)$
d) Force increases by 9 $(1/\ 1/3^2)$
Q4 a) Force doubles
b) Force triples
c) Force decreases by 1/2
d) Force increases by 6 times
Q5 The force of the earth on the moon is equal in magnitude to the force of the moon on the earth.
Q6 Discussion
Q7 No. The law describes the factors determining the size of the gravitational force, but does not propose a mechanism by which it works.
Q8 a) Force decreases by 1/4
b) Force decreases by 1/8
c) Force increases by 24 times
Q9 Discussion
Q10 a) 2.0×10^{20}N They are the same size forces.
b) 4.3×10^{20}N They are the same size forces.
Q11 Discussion
Q12 Discussion
Q13 The law of gravitation, applied to the perturbations of Uranus, indicated the existence of a planet beyond Uranus, and even lead to a prediction if its mass and orbit.
Q14 Discussion
Q15 Discussion

Answers to End-of-Chapter Problems

Chapter 6

6.1 1.8×10^4 lunks
6.2 Each season the sun changes its position on the ecliptic by moving 90° east. The stars in the region of the sky east of the sun pass overhead in the daylight hours and are not observed.
6.3 a) Latitude of observer = altitude of Polaris
b) Hint: Consider altitude of the sun at noon and also the sun's declination on the date of observation. (See handbook, page 94)
6.4 15°/hr. westward
6.5 1°/day eastward
6.6 Discussion
6.7 Approx. 13°/day eastward
6.8 Discussion
6.9 2.68×10^4 km
6.10 Ptolemy made *all* these assumptions.
6.11 Discussion
6.12 Discussion
6.13 Discussion
6.14 Discussion
6.15 Discussion

Chapter 7

7.1 You might consider some of the ideas of relativity theory as presented by Mr. Tomkins in Wonderland. George Gamow — published by Cambridge University Press.
7.2 Discussion
7.3 a) 1.68×10^3 m/hr.
b) This push due to rotation of the earth may be used if the rocket is launched eastward.
c) 1.01×10^5 m/hr.
7.4 See handbook page 115.
7.5 Discussion
7.6 See handbook page 123.
7.7 Discussion
7.8 Discussion
7.9 1.4×10^5 AU
7.10 Discussion

Chapter 8

8.1 Discussion
8.2 Discussion
8.3 Discussion
8.4 4%
8.5 a) 17.9AU
b) 35.3AU
c) 0.54AU

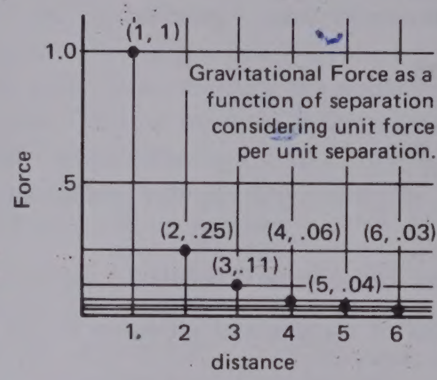
8.6 249 years
8.7 K = 1.0 for all planets

8.8 $1.41 \times 10^{-2} \dfrac{\text{days}^2}{(\text{Jupiter's radius})^3}$ to within 1%

8.9 Discussion
8.10 Jupiter does not show phases
8.11 Discussion
8.12 Discussion
8.13 Discussion
8.14 Discussion
8.15 Discussion

Chapter 9

9.1 Discussion
9.2



9.3 a) Force decreases by 1/100
b) Force decreases by 1/9
c) Force increases by 100
d) Force increases by 100
9.4 Discussion
9.5 $\dfrac{F\,\text{sun}}{F\text{moon}} \sim 200{:}1$

You might wonder then why the moon is the major tide producing force and not the sun. You could check the reason for this in an encyclopedia (eg. *World Book*, Vol. 19 pg. 220, 1973 edition).
9.6 Discussion
9.7 Discussion
9.8 a) 5.52×10^3 g/m^3
b) Discussion
9.9 Discussion
9.10 Discussion
9.11 Discussion
9.12 Discussion
9.13 Discussion
9.14 Discussion
9.15 Discussion
9.16 $\dfrac{\text{Mass of Jupiter}}{\text{Mass of Sun}} = \dfrac{1}{320}$

PHYSICS: A HUMAN ENDEAVOUR

Motion
Motion In The Heavens
Energy and the Conservation Laws
The Nature of Light and Sound
Electricity
The New Physics

HOLT, RINEHART AND WINSTON OF CANADA, LIMITED TORONTO MONTREAL